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Computer Modeling of a Fusion Plasma

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Computer Modeling of a Fusion Plasma

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Abstract

Progress in the study of plasma physics and controlled fusion has been profoundly influenced by dramatic increases in computing capability. Computational plasma physics has become an equal partner with experiment and traditional theory. This presentation illustrates some of the progress in computer modeling of plasma physics and controlled fusion.

The growth and maturation of experimental and theoretical plasma physics since World War II has been aided profoundly by the growth of computing capability. With the development of modern supercomputing facilities at universities, national laboratories, and industrial research centers, computational plasma physics has emerged as an equal partner with experiment and theory in plasma physics research. The use of computers in the design, operation, modeling, and theory of laboratory and naturally occurring plasmas and in plasma applications has become ubiquitous. With the development of computational plasma physics as a discipline leading to improved simulation algorithms and the continued exponential growth of supercomputing performance, the ability to simulate three-dimensional, nonlinear, and time-dependent plasma phenomena with increasingly realistic physical parameters has also grown exponentially. Computer modeling is helping researchers to better understand plasma behavior, is giving significant guidance in the directions to take experiments, and in consequence is accelerating discovery in all areas of plasma physics research.

The matter that occupies most of the volume of the universe is in the plasma state. A plasma is a relatively tenuous gas consisting of ions and electrons (and sometime neutrals as well), whose dynamics is dominated by classical electrodynamics. Examples of plasmas are flames, sparks, lightning, the solar corona, the earth's ionosphere and magnetosphere, most of interstellar space, electrical discharge tubes, and fusion plasmas in controlled fusion experiments and thermonuclear detonations. Controlled fusion experiments employ inertially confined plasmas and magnetically confined plasmas whose behavior depends in detail on plasma physics.

Plasma physics is complicated and notoriously difficult to understand and model completely. A direct numerical approach based on a first-principles-based equation sets typically fails because of the enormous range of time and space scales in most plasmas. This has been a major obstacle to researchers in the plasma sciences and in particular in controlled fusion who are often confronted with extraordinarily complex phenomena that may be nonlinear and kinetic, and may exhibit variations in three spatial dimensions and time. With the growth and exploitation of computing capability to aid plasma physics research (increased speed of the microprocessors, increased memory and memory bandwidth, and the introduction of massively parallel computers), a new sub-discipline of plasma physics has been born, viz., computational plasma physics. Computational plasma physicists have developed the science and art of plasma simulation.[1-4] Accompanying the growth of computing hardware capability has been the equally impressive growth of the software, i.e., the development of efficient numerical algorithms with which to solve the plasma physics equations. Selected examples of current computer modeling of plasmas in controlled fusion (magnetically confined and inertially confined plasmas), advanced plasma-based particle acceleration, and plasma devices are presented in the accompanying illustrated examples.

The future of computer modeling of plasmas is likely to be an extrapolation of its current state. The relevance of computer simulations of plasmas to experiment and plasma science in general is now well established and will continue to grow. The range of space and time scales in most plasmas will still far exceed the capabilities of hardware and algorithms to do direct, first-principles simulation in 3D + time for some significant time period extending into the future. However, hardware capability (cpu speed, memory size and bandwidth, etc.) and algorithms will continue to improve dramatically so that researchers will be able to perform ever bigger and more realistic simulations. The cost of doing leading-edge (albeit “bleeding-edge”) computing will likely continue to remain small (≤ $20-$30M for the supercomputer) compared to the capital cost of a fusion ignition experiment (~$1-$2B). Thus, a relatively inexpensive, but increasingly *realistic* simulation capability will continue to have immense leverage on relatively expensive experiments.

The author is grateful to numerous researchers for sharing their research and visuals that went into this presentation: R. Berger, C.K. Birdsall, A. Dimits, E. Doyle, A. Friedman , G. Hammett, J. Harte, S. Jardin, T. Katsouleas, A. B. Langdon, B. Lasinski , J.-N. Leboeuf, Z. Lin, W. Mori, W. Nevins, T. Rhodes, T. Rognlien, R. Stambaugh, C. Still, L. Suter, W. Tang, J. Verboncoeur, X. Xu, G. Zimmerman. This work was performed for the U.S. Department of Energy under Contract No. W-7405-ENG-48 at the University of California Lawrence Livermore National Laboratory and is part of the Plasma Microturbulence Project sponsored by the Office of Fusion Energy Sciences.

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[1]B. Alder, S. Fernbach, M. Rotenberg, and J. Killeen, *Methods in Computational Physics,* Academic Press, NY., Vol. 9, 1970 and Vol. 16, 1976.

[2]R.W. Hockney and J. Eastwood, *Computer Simulation Using Particles*, McGraw-Hill, NY, 1981.

[3]C.K. Birdsall and A.B. Langdon, *Plasma Physics Via Computer Simulation, ,* McGraw-Hill, NY, 1985.

[4]J.U. Brackbill and B.I. Cohen, *Multiple Time Scales* Computational Techniques, Vol. 3, Academic Press, Orlando, 1985.

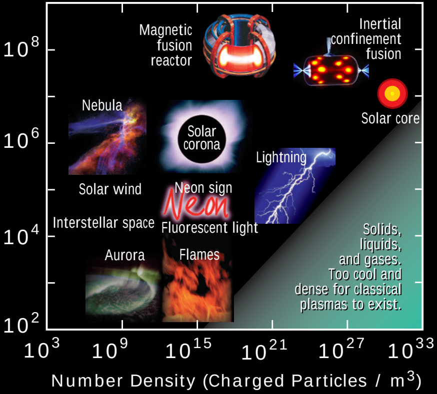
Computer Modeling of a Fusion Plasma -- Outline

1. Introduction
   - -- Definition of a plasma
   - -- Plasma simulation basics and the computational challenge
2. The growth of computing capability
3. State-of-the-art plasma simulation – examples
   - -- Plasma-based high-energy accelerators
   - -- Plasma devices
   - -- Heavy-ion fusion
   - -- Laser fusion
   - -- Magnetic fusion

PLASMAS – THE 4th STATE OF MATTER

CHARACTERISTICS OF TYPICAL PLASMAS

Plasmas consist of freely moving charged particles, i.e., electrons and ions. Formed at high temperatures when electrons are stripped from neutral atoms, plasmas are common in nature. For instance, stars are predominantly plasma. Plasmas are a "Fourth State of Matter" because of their unique physical properties, distinct from solids, liquids and gases. Plasma densities and temperatures vary widely.

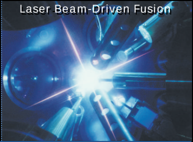


CREATING THE CONDITIONS FOR FUSION

PLASMA CONFINEMENT AND HEATING

Confinement:

Fusion requires high temperature plasmas confined long enough at high density to release appreciable energy.

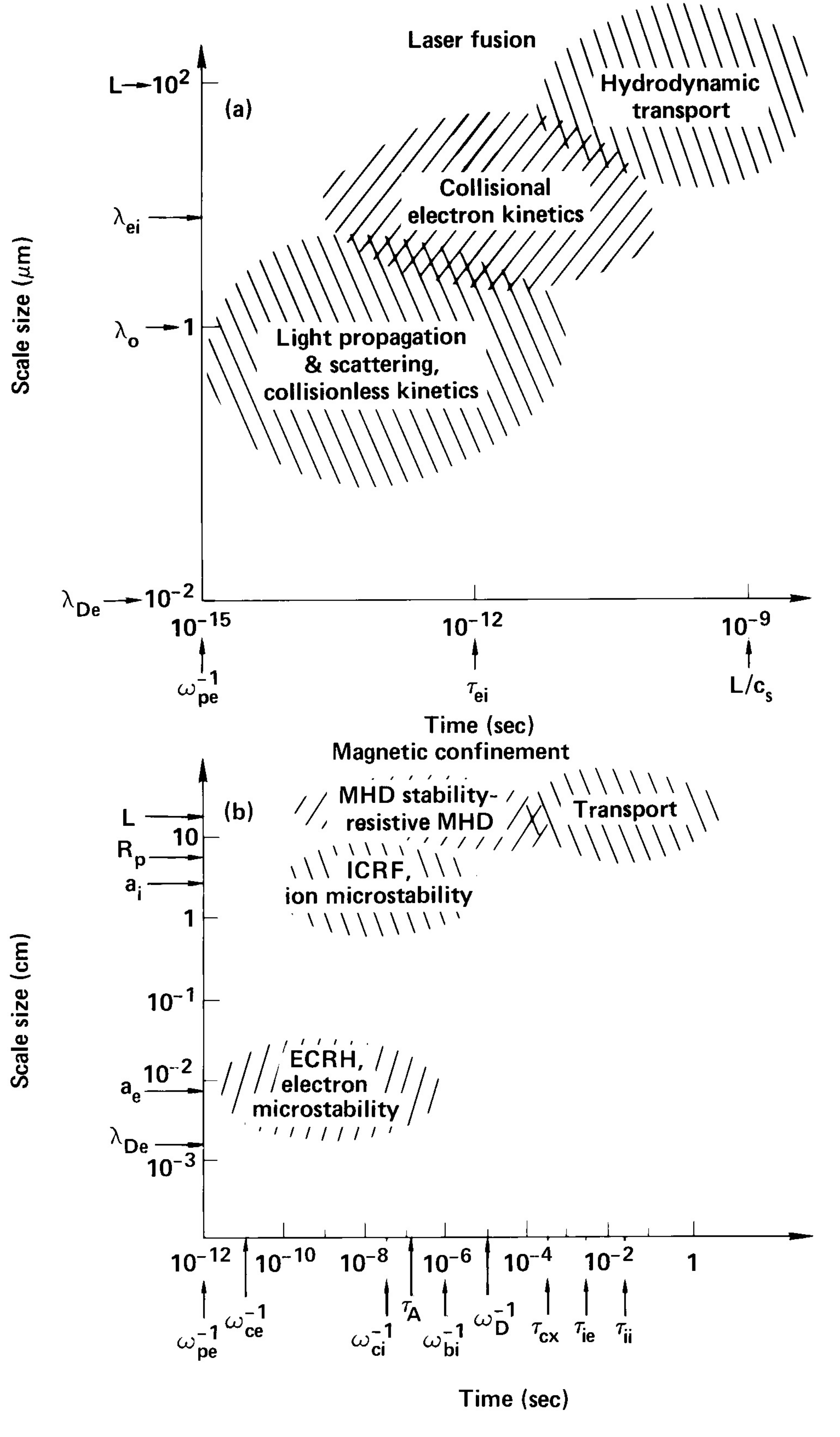
	Gravity	Magnetic Fields	Inertia
			
Typical Scales:	<--------- Size: 10^{19} m----------> Plasma Duration: 10^{15} - 10^{18} s	<---------- Size: 10 m ----------> Plasma Duration: 10^{-2} to 10^{6} s	<------------ Size: 10^{-1} m ------------> Plasma Duration: 10^{-9} to 10^{-7} s
Heating Mechanisms:	• Compression • Fusion Product Energy	• Electromagnetic Waves • Ohmic Heating (electricity) • Neutral Beam Injection (beams of atomic hydrogen) • Compression • Fusion Product Energy	• Compression (Implosion driven by laser or ion beams, or by x rays from laser or ion beams) • Fusion Product Energy

Plasma Simulation – Basics

- Plasmas of fusion interest are dominated by classical electrodynamics and a combination of fluid and kinetic phenomena.
- Self-consistent equations set (typically 2D or 3D in space and possibly time dependent):
- Nonlinear partial differential equations describing conservation of momentum, energy, etc., describing the plasma as a fluid (or non-conservation equations if sources and sinks are present) with electromagnetic forces.

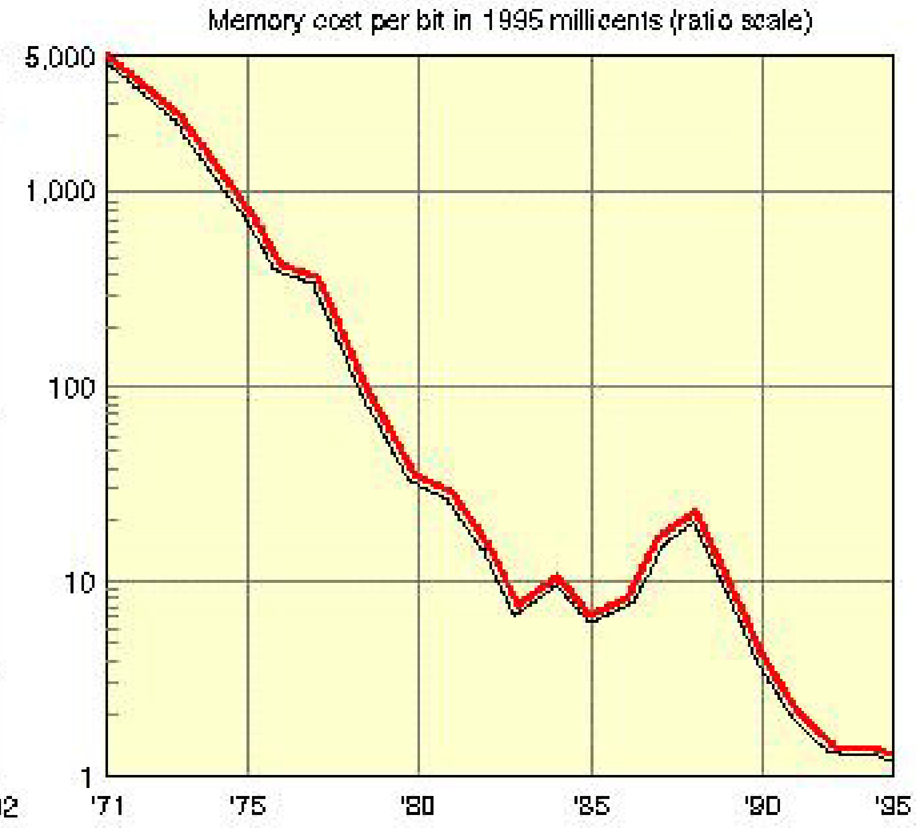
  Alternatively, a set of ordinary nonlinear differential equations for an ensemble of “particles” moving through a computational grid.
- The plasma fluid or particle equations provide current and charge density sources computed on the grid for use in Maxwell’s equations (possibly reduced), which determine the electromagnetic fields self-consistently.

Refs. – *Methods in Computational Physics* (B. Alder, S. Fernbach, M. Rotenberg, and J. Killeen, ed.), Academic Press, NY., Vol. 9, 1970 and Vol. 16, 1976; R.W. Hockney and J. Eastwood, *Computer Simulation Using Particles,* McGraw-Hill, NY, 1981; C.K. Birdsall and A.B. Langdon, *Plasma Physics Via Computer Simulation, ,* McGraw-Hill, NY, 1985; *Multiple Time Scales* (J.U. Brackbill and B.I. Cohen,ed.)*,* Computational Techniques, Vol. 3, Academic Press, Orlando, 1985.



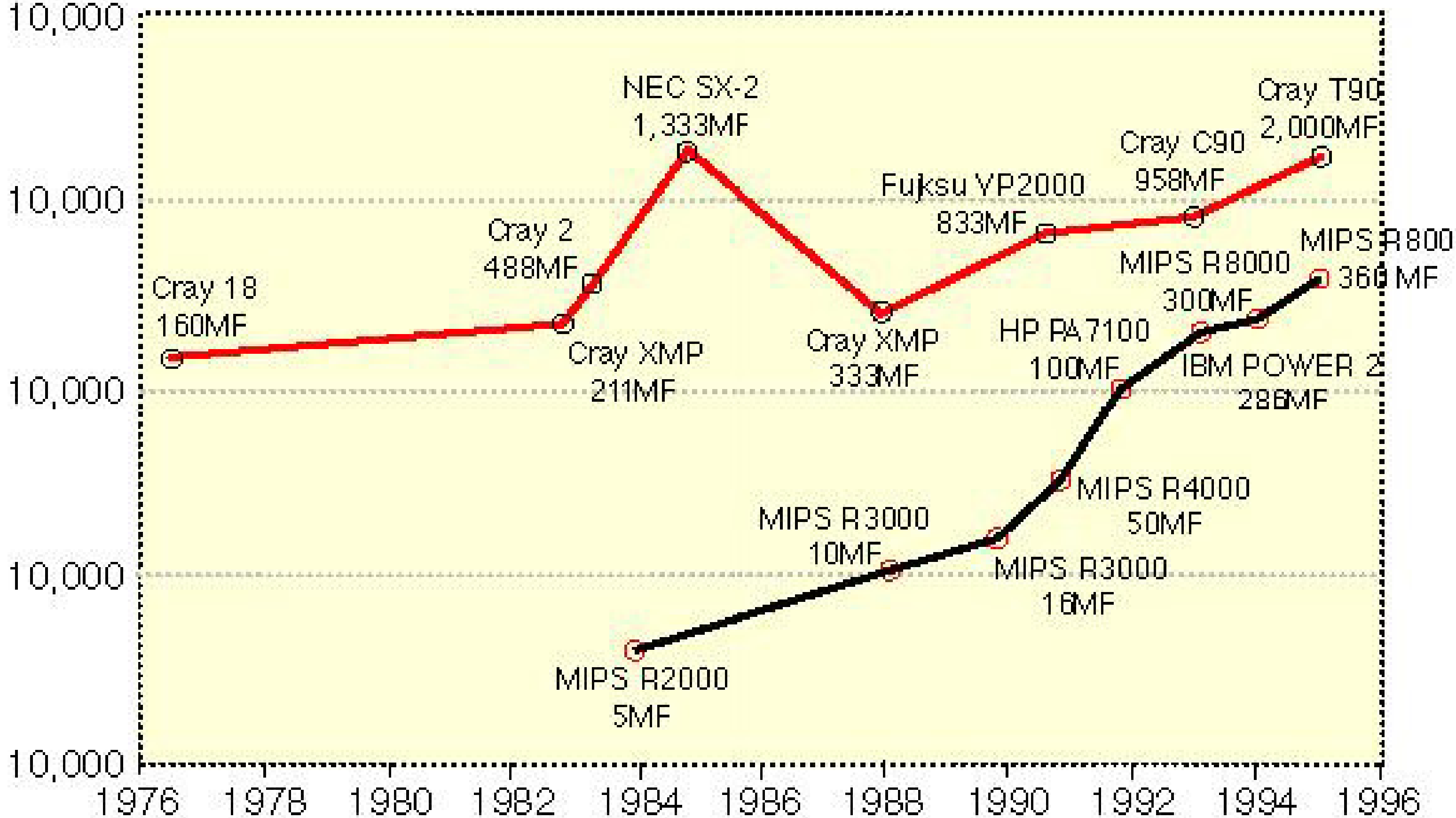
Laser fusion
(a)
Hydrodynamic transport
Collisional electron kinetics
Light propagation & scattering, collisionless kinetics
Scale size (μm)
L → 10^2
λ_{ei}
λ_o → 1
λ_{De} → 10^{-2}
10^{-15}
10^{-12}
10^{-9}
ω_{pe}^{-1}
τ_{ei}
L/c_s
Time (sec)
Magnetic confinement
(b)
MHD stability-resistive MHD
Transport
ICRF, ion microstability
ECRH, electron microstability
Scale size (cm)
L
10
R_p
a_i
1
10^{-1}
a_e
10^{-2}
λ_{De}
10^{-3}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
ω_{pe}^{-1}
ω_{ce}^{-1}
ω_{ci}^{-1}
τ_A
ω_{bi}^{-1}
ω_D^{-1}
τ_{cx}
τ_{ie}
τ_{ii}
Time (sec)

Moore's First Law

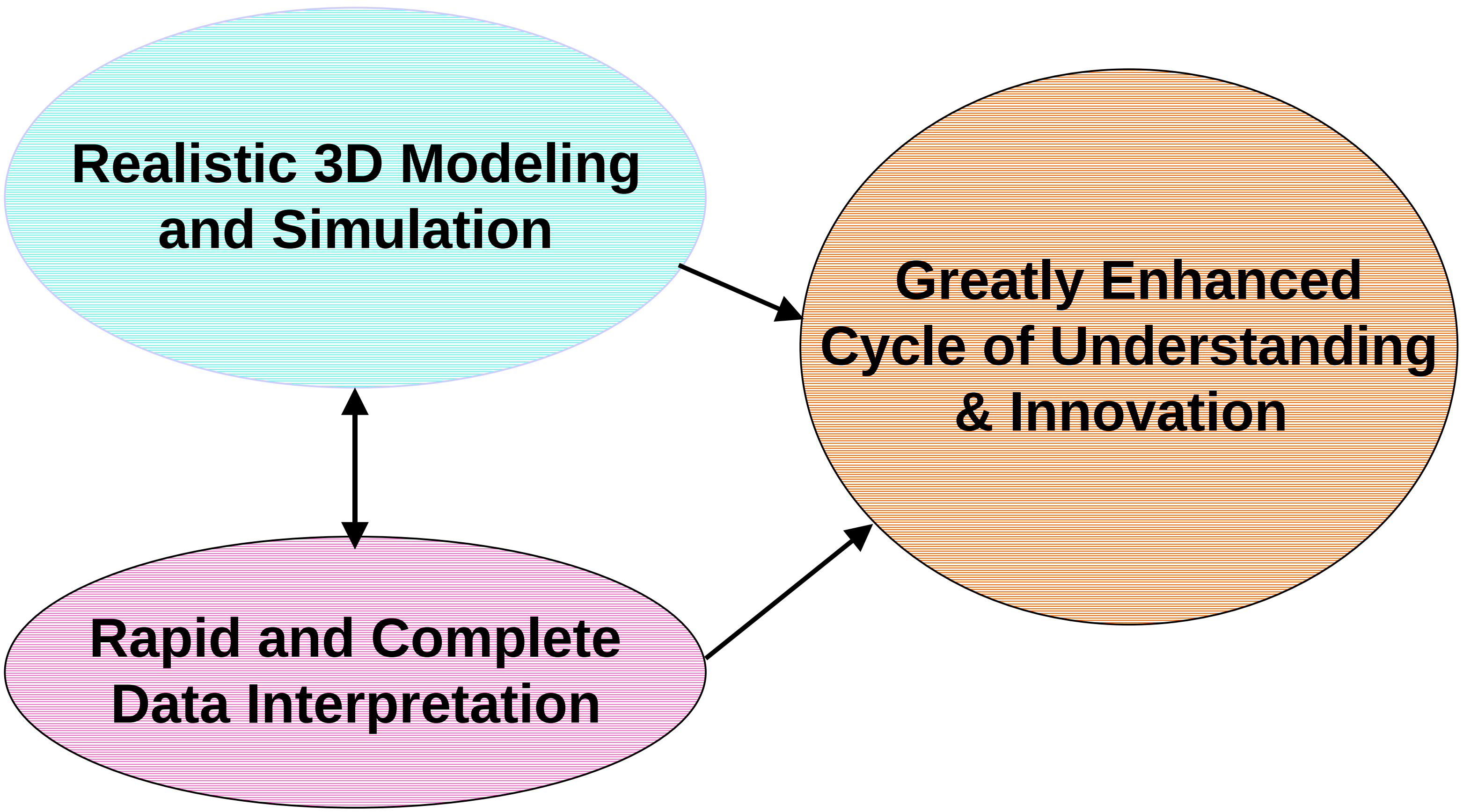


Source: VLSI Research Inc.

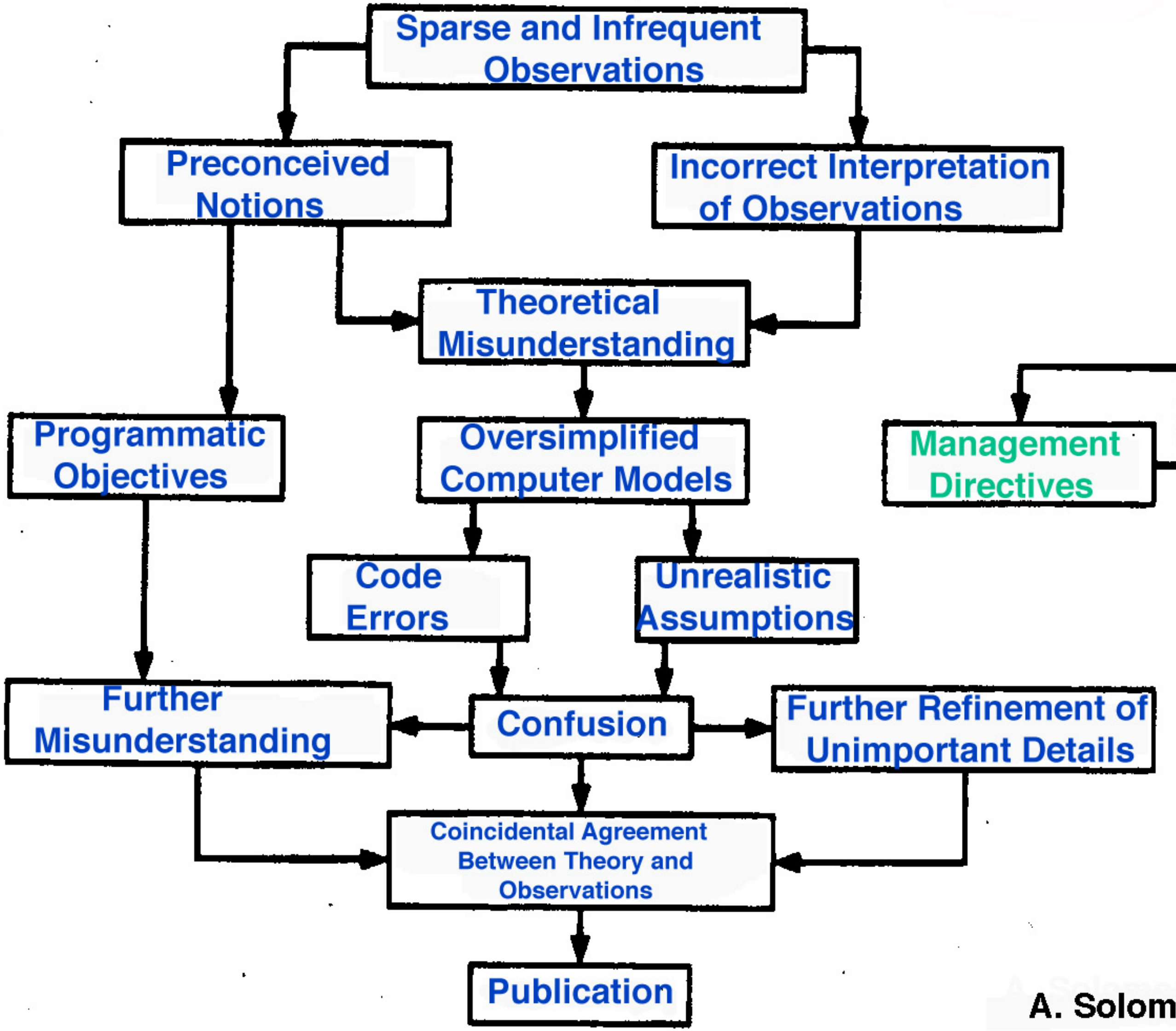
Microprocessors vs. Vector Supercomputers (ca. 1994)



IT / ADVANCED COMPUTING ENABLES:



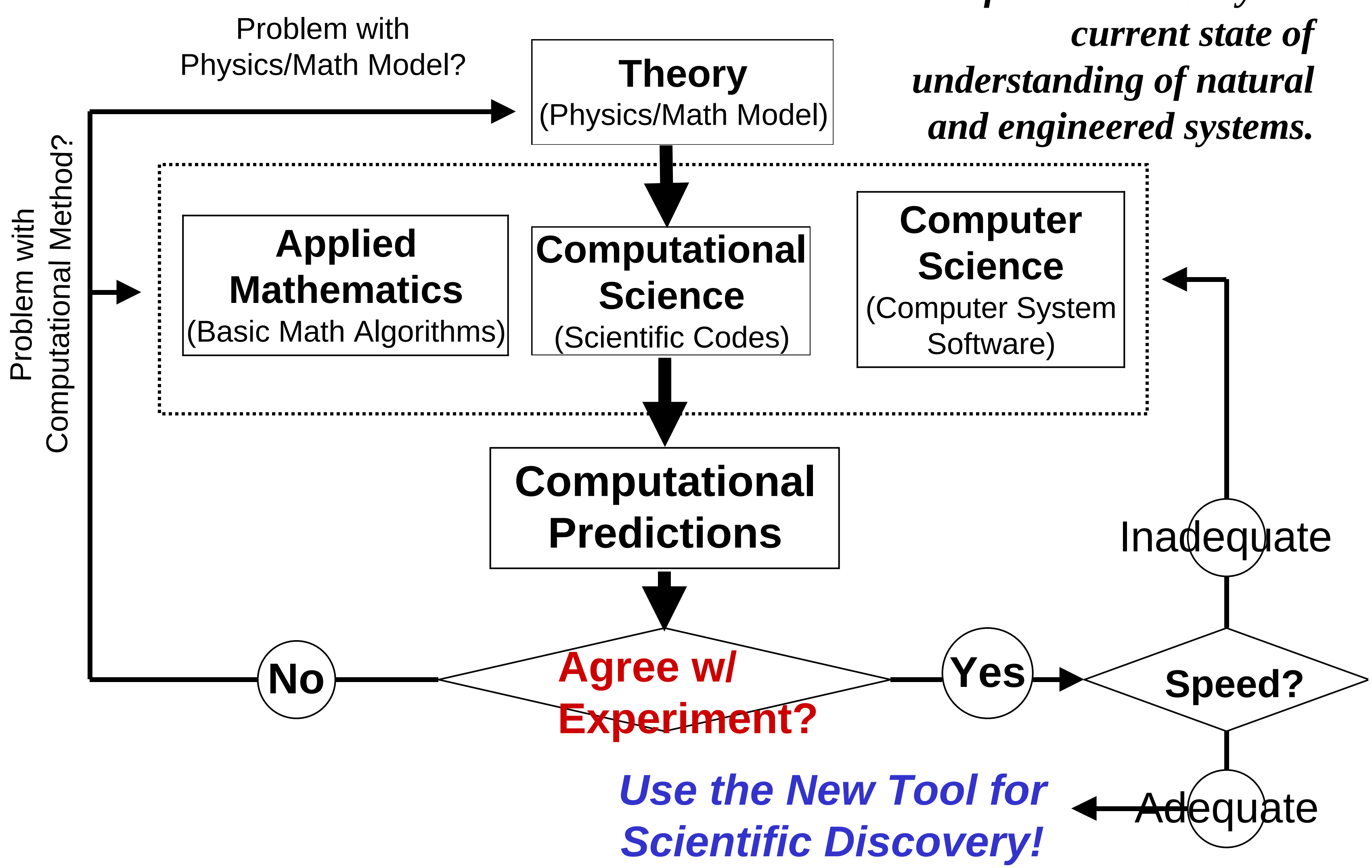
Flowchart: Computer Model Development



A. Solomon, ORNL

Scientific Code Development

Scientific codes embody the current state of understanding of natural and engineered systems.



Plasma-based high-energy accelerators

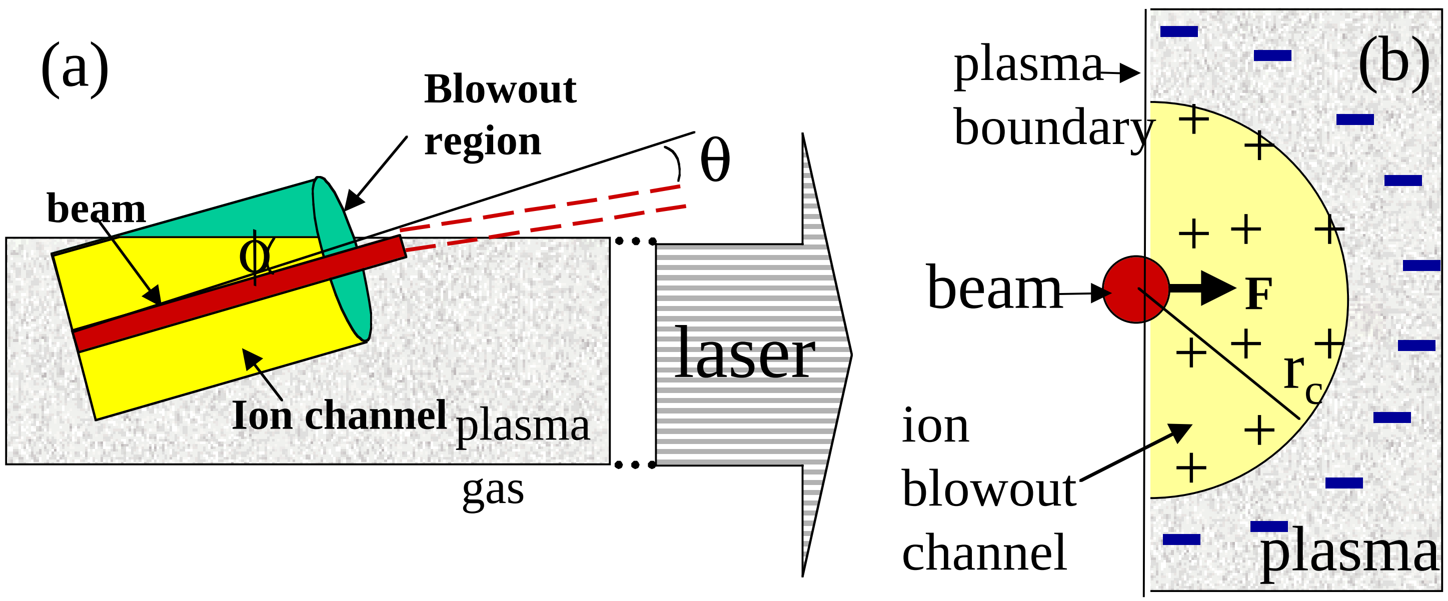
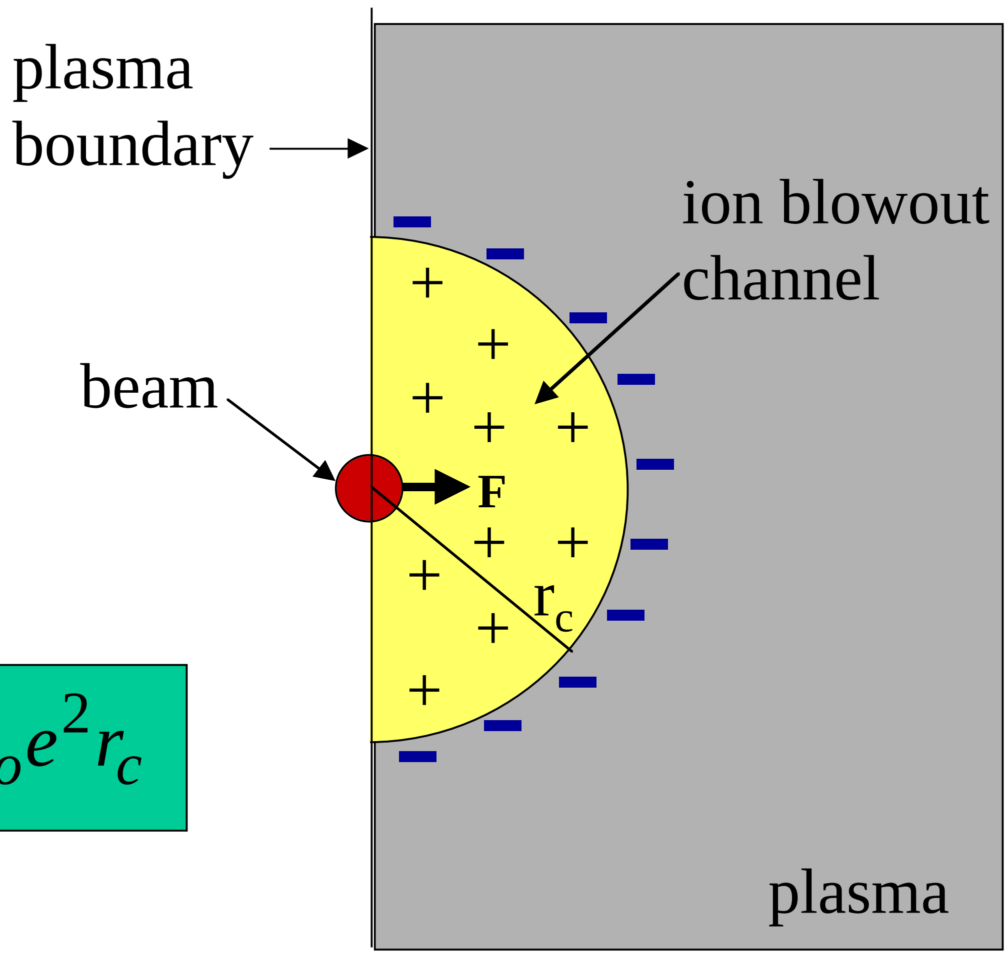


Figure 1. Schematic of laser steering concep:. a) side view and b) front view of beam and plasma illustrating how asymmetric blowout creates a net deflection force. -T. Katsouleas+E-157 Coll., USC, UCLA, and SLAC

Asymmetric blowout creates net deflection force

Front view of beam and plasma:



$$F = 2n_o e^2 r_c$$

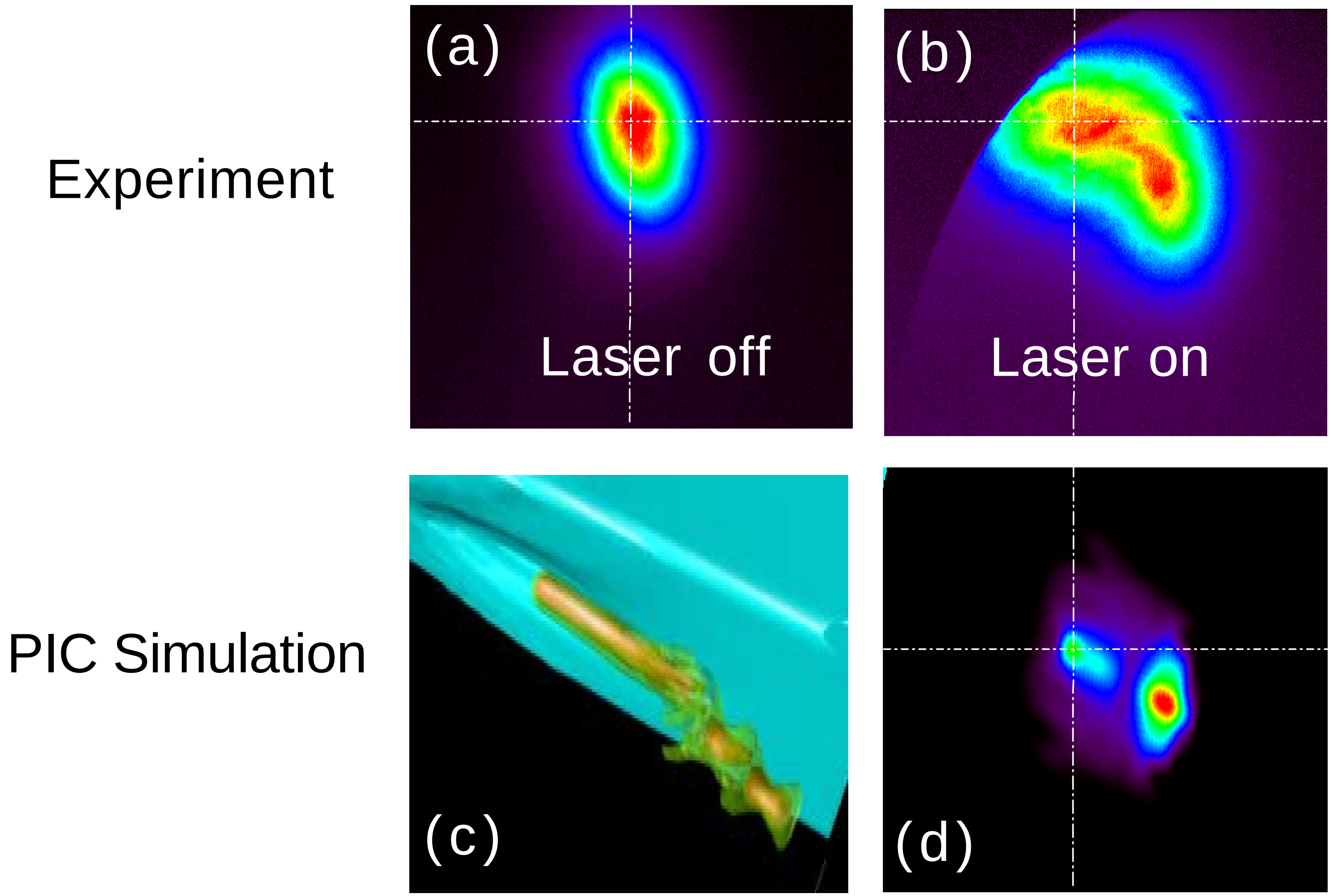
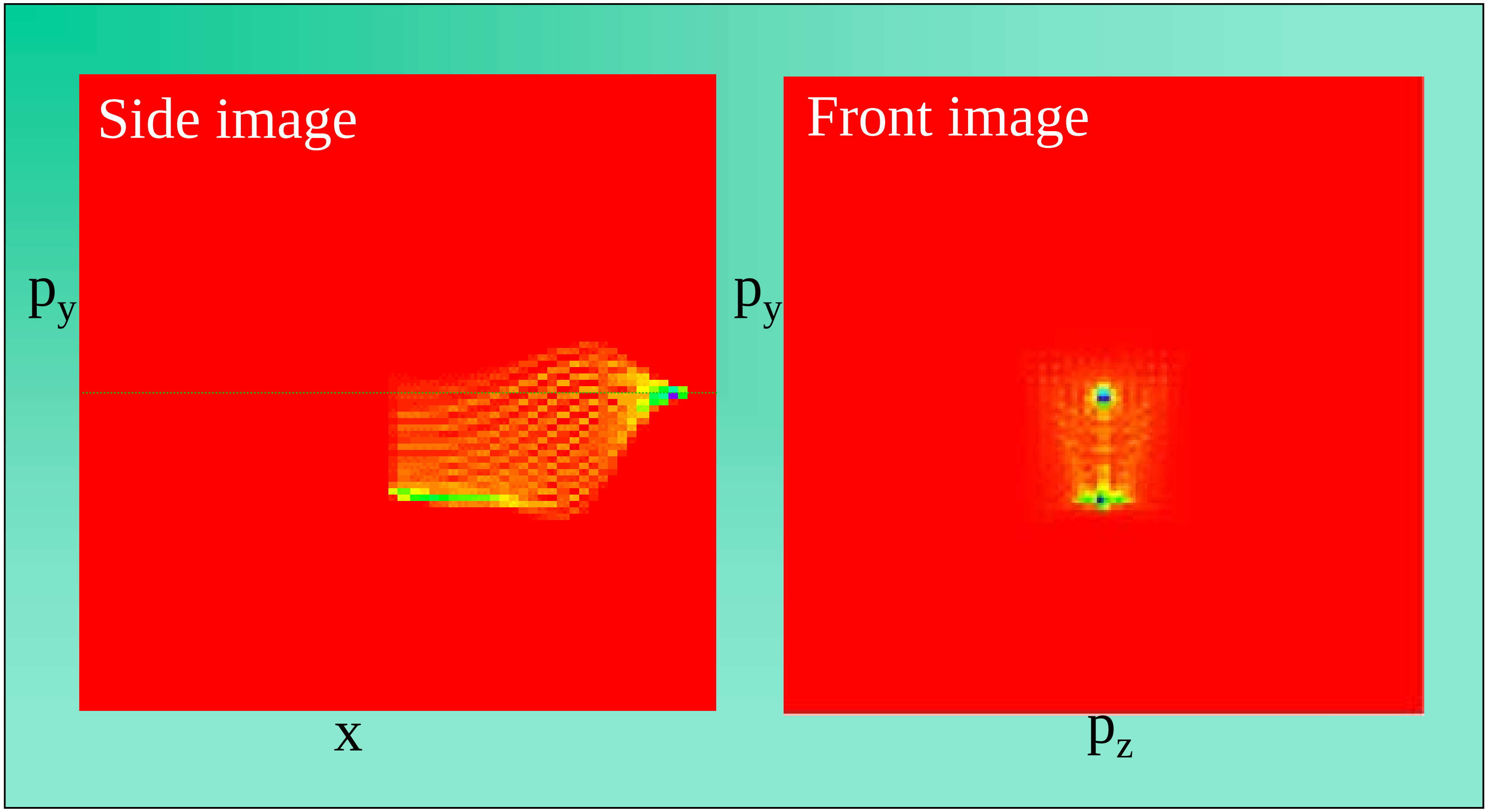


Fig. 2. Images of the electron beam showing refraction of a portion of the beam: a) experiment, laser off, b) experiment, laser on at an angle ϕ of 1mrad to the beam, c) PIC simulation of electron beam, side view with plasma shown (blue), and d) PIC simulation, head on view corresponding to (b). Cross hairs show undeflected beam location.

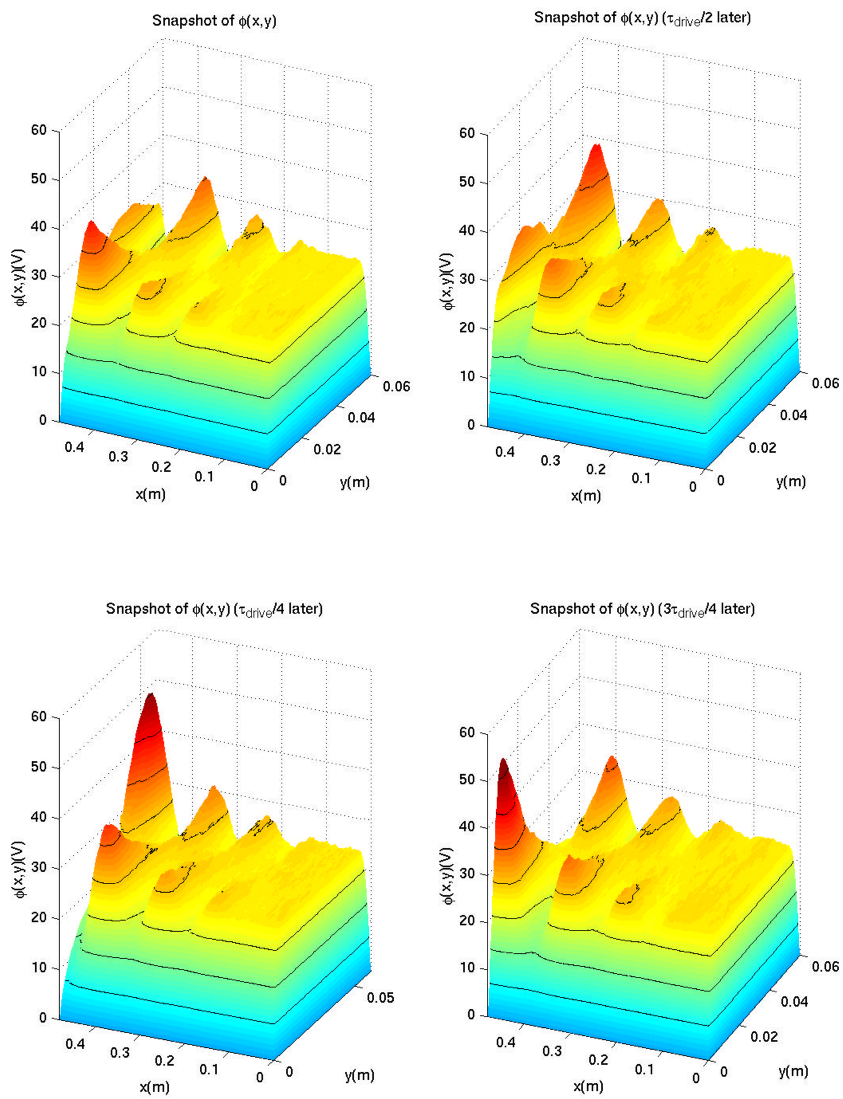
3-D Simulations show head goes straight, body is steered



Plasma devices

Plasma Loaded Waveguide

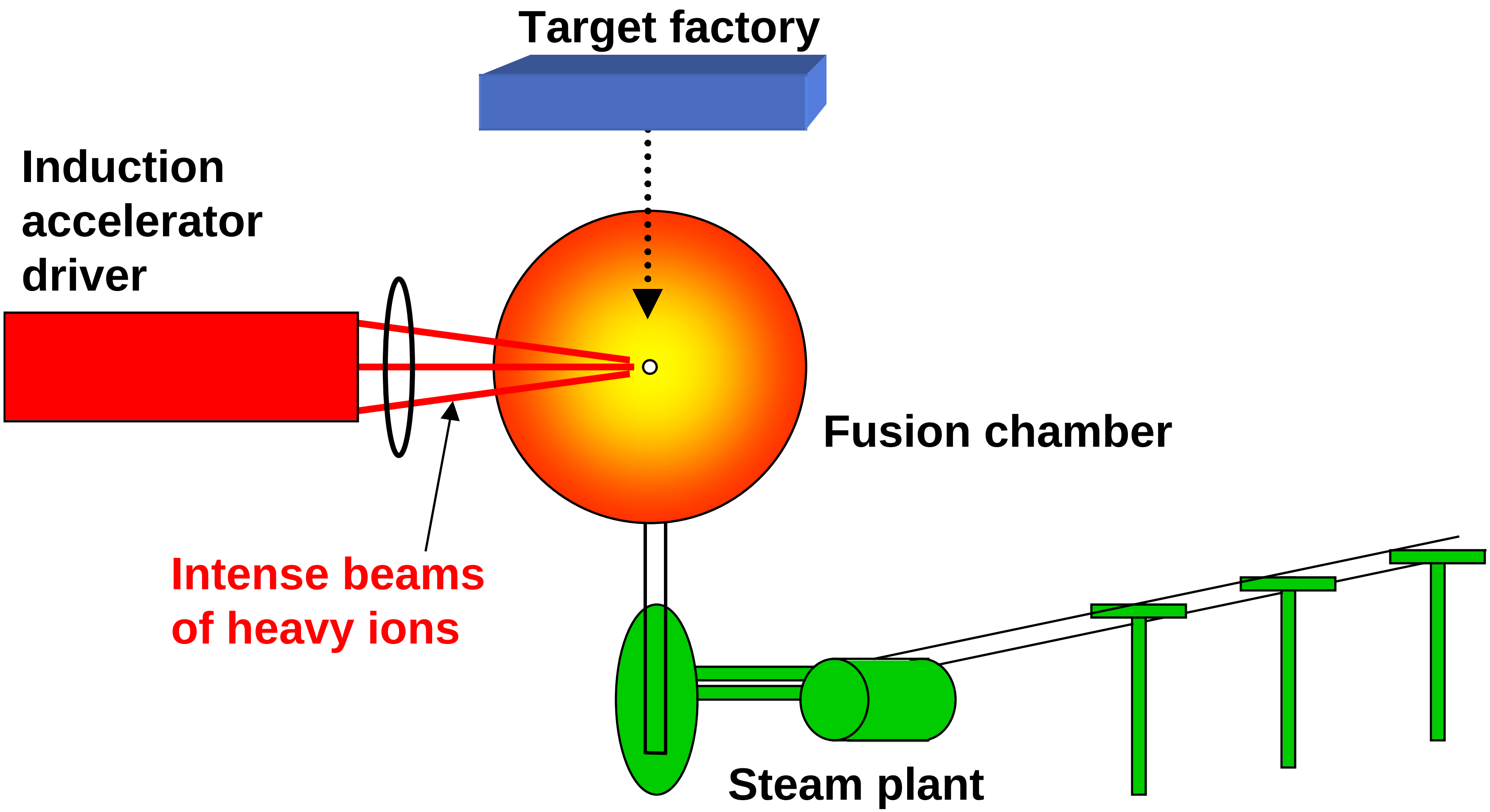
- Plasma loaded waveguides are used to generate and propagate microwaves.
- Propagation of the electron series resonant surface wave in a parallel plate waveguide is shown.
- Wave is excited by an antenna at *x=0.5m* specifically designed to launch this mode.



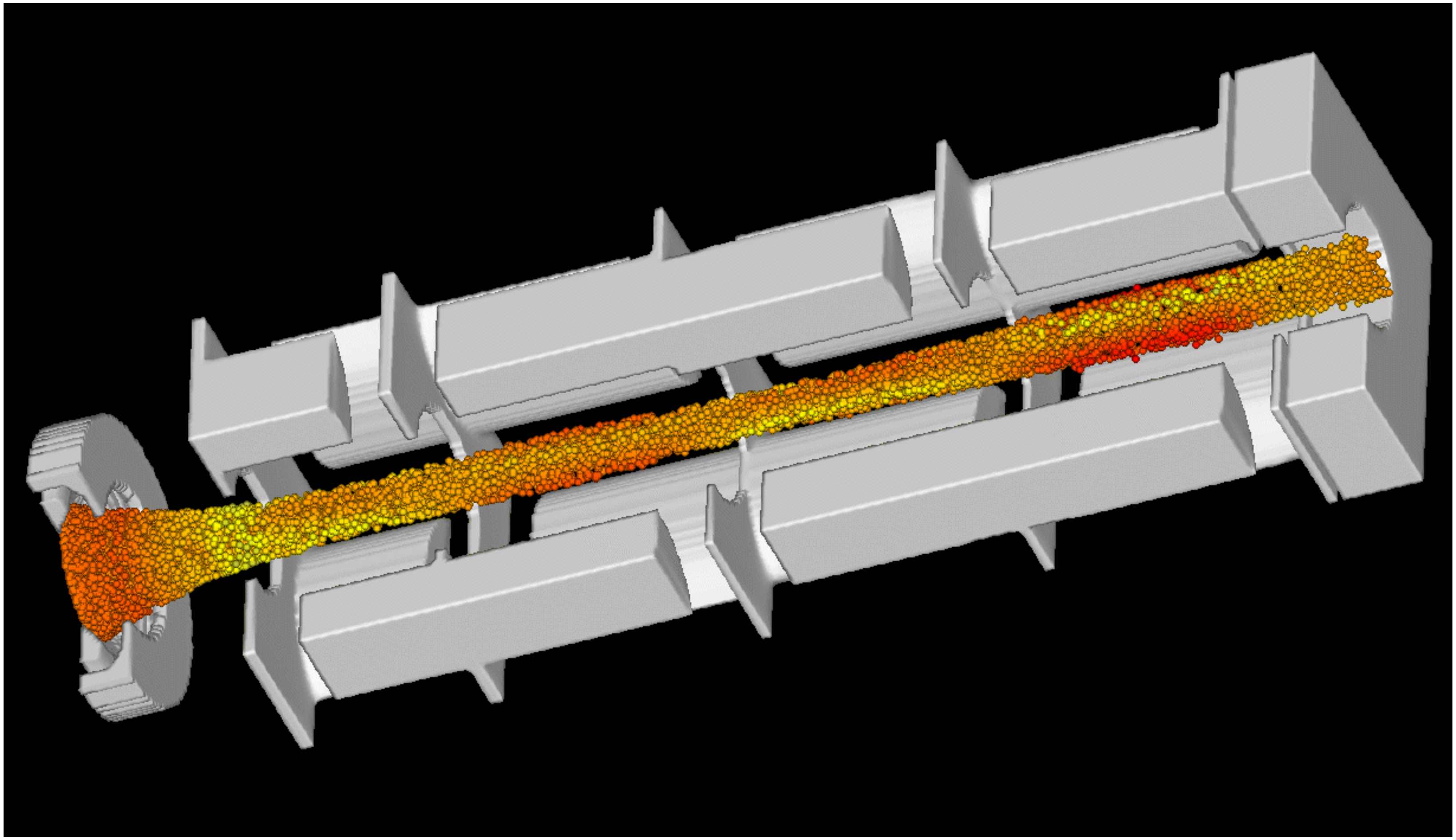
- J. Verboncoeur and C.K. Birdsall, UC Berkeley

Heavy-ion fusion

Heavy-Ion beam-driven inertial Fusion (HIF) power plants will consist of four parts



WARP3d PIC simulations quantified "energy effect" in 2 MV, 0.8 A electrostatic quadrupole injector



Energy effect: focusing potentials approaching ± 200 kV are not small relative to beam energy

Color of ion denotes energy relative to on-axis value at each longitudinal position

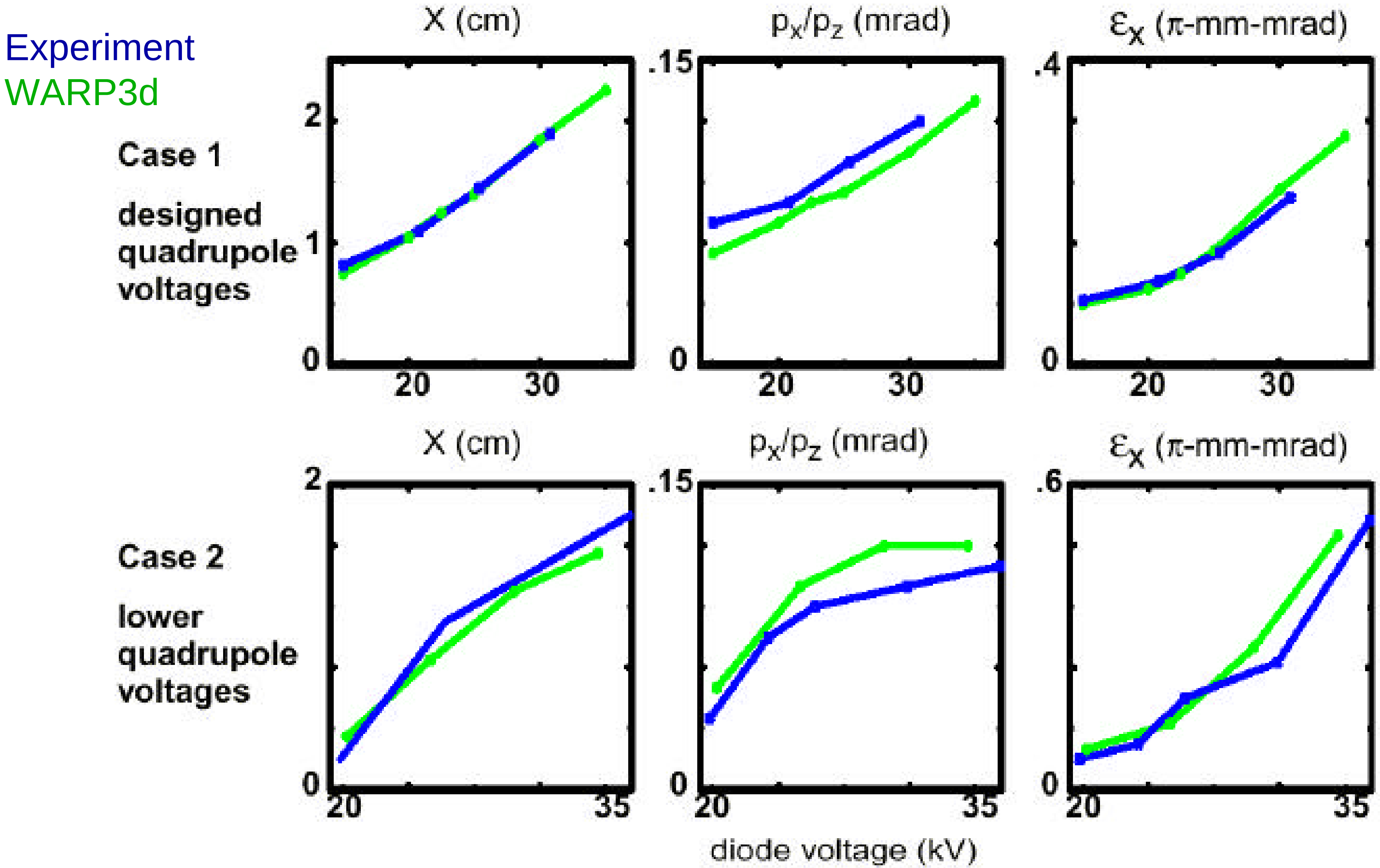
Details of 10 GeV, 3 kA simulations

Some beam and simulation parameters:

$A_{ion} = 130$	$\sigma = 70°$	$l_{hlp} = 3$ m
$E_{kin} = 10$ GeV	$\sigma_0 = 15°$	$\Delta t = 3.3\times10^{-10}$ s
$v_b = 1.2\times10^8$ m/s	$a_0 = 3.2$ cm	steps/period = 150
$I_b = 3$ kA	$b_0 = 1.8$ cm	$\Delta z = 2.34$ cm
$l_b = 10.8$ m	$x_w = 5$ cm	$\Delta x = 1.56$ mm

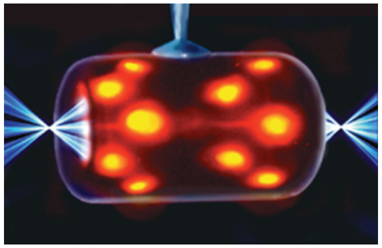
640K particles, 32x32x512 mesh, 75000 steps
1.77 hours on 128 Cray-T3E CPUs

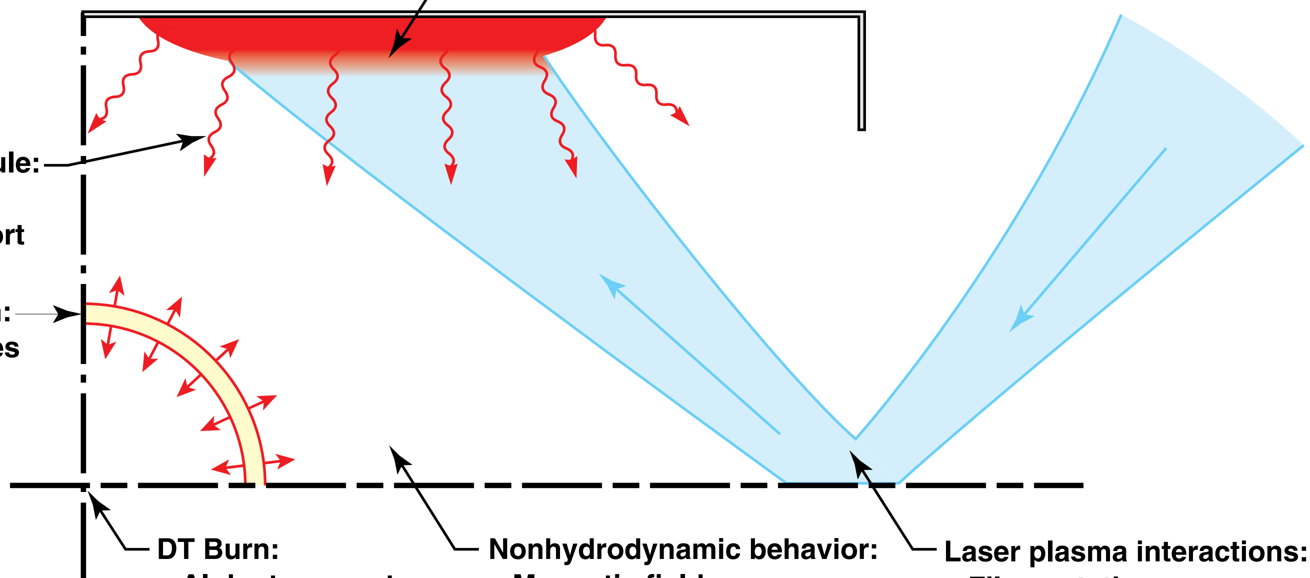
Comparison between scaled ESQ experiment and WARP3d



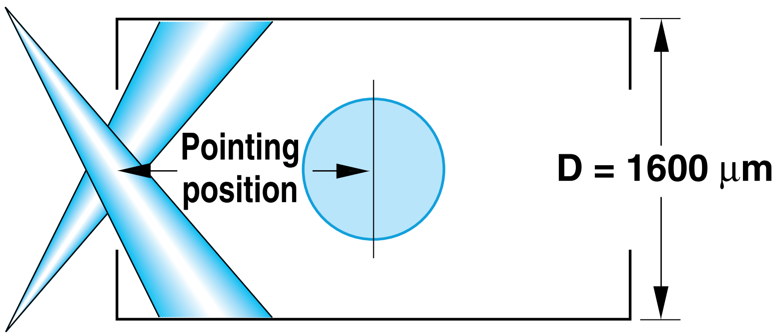
Laser fusion

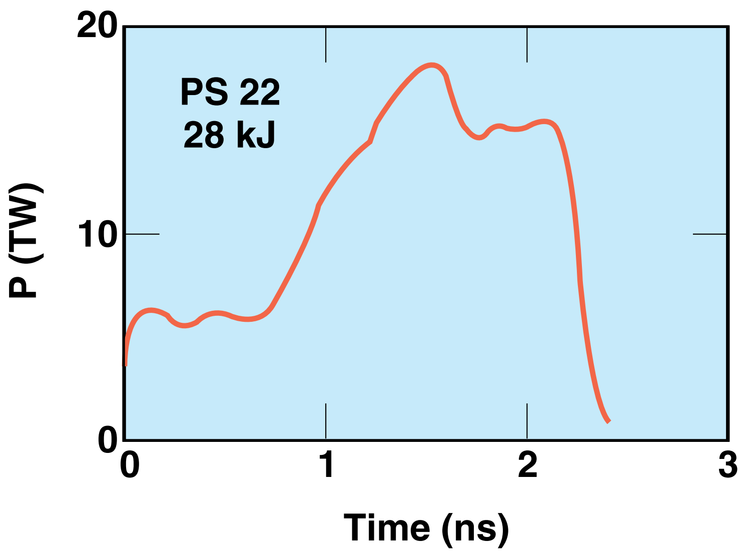
Simulating indirect drive ICF experiments requires highly integrated computational modeling

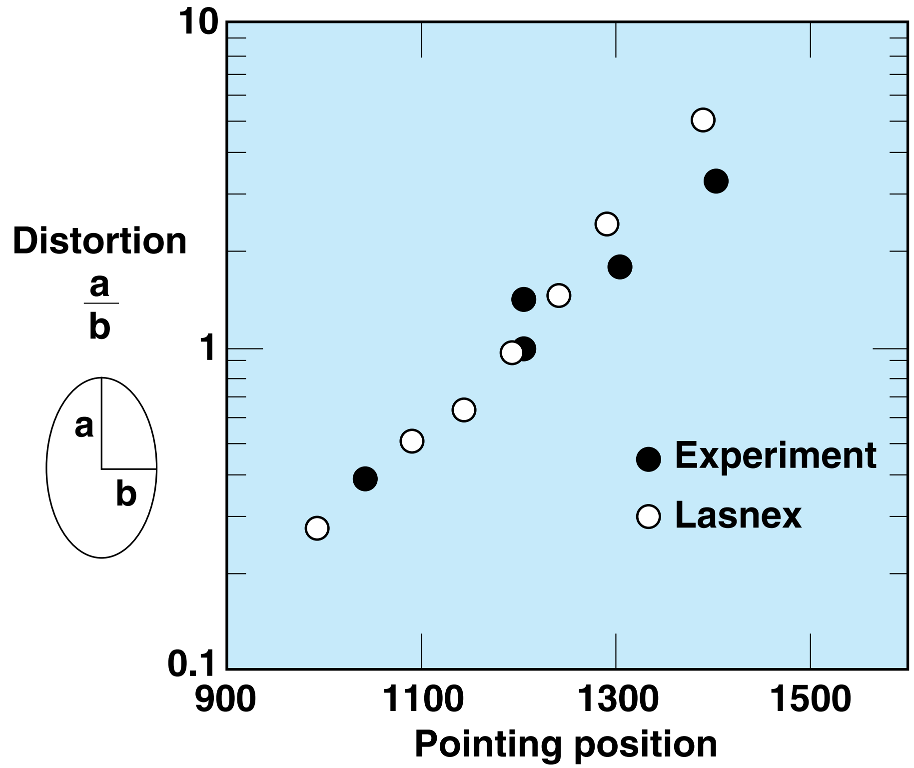




Lasnex calculations do an excellent job of modeling capsule distortion for experiments in which the laser pointing is varied



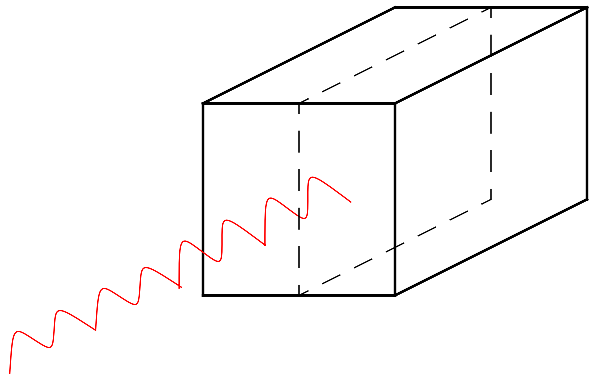




G. Zimmerman, LLNL

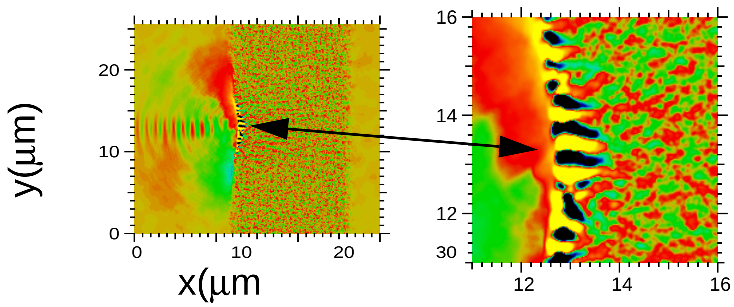
Previous ZOHAR (2-D PIC) simulations demonstrate that MPP and 3-D modeling are essential.

10^{21} W/cm^2, $50n_c$



- Simulation of a 2-D slice of a high intensity short pulse laser interacting with an overdense plasma slab.

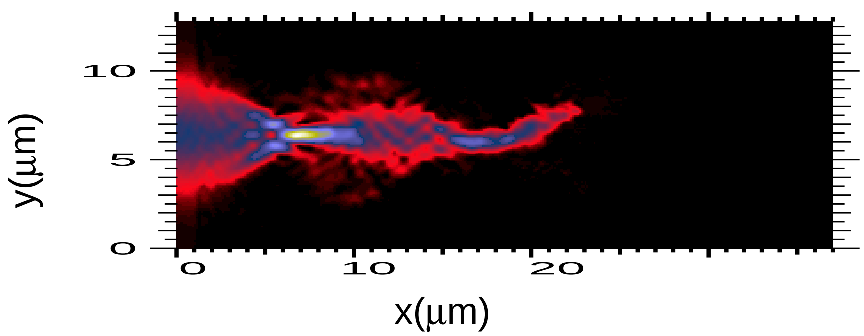
$(B_z)_{dc}$ at 0.1 ps. Peak is 10^9 G



- Central region is enlarged to emphasize the filamentary structure.

- On a single processor DEC, had 12 million particles and used ~ 400 hours to get to 1.2 ps.

Poynting flux, $(P_x)_{dc}$, at 1.2 ps



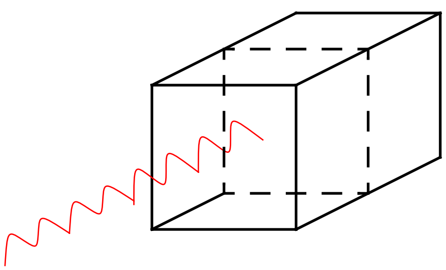
- There is evidence of a “kinking” instability in the propagation direction.

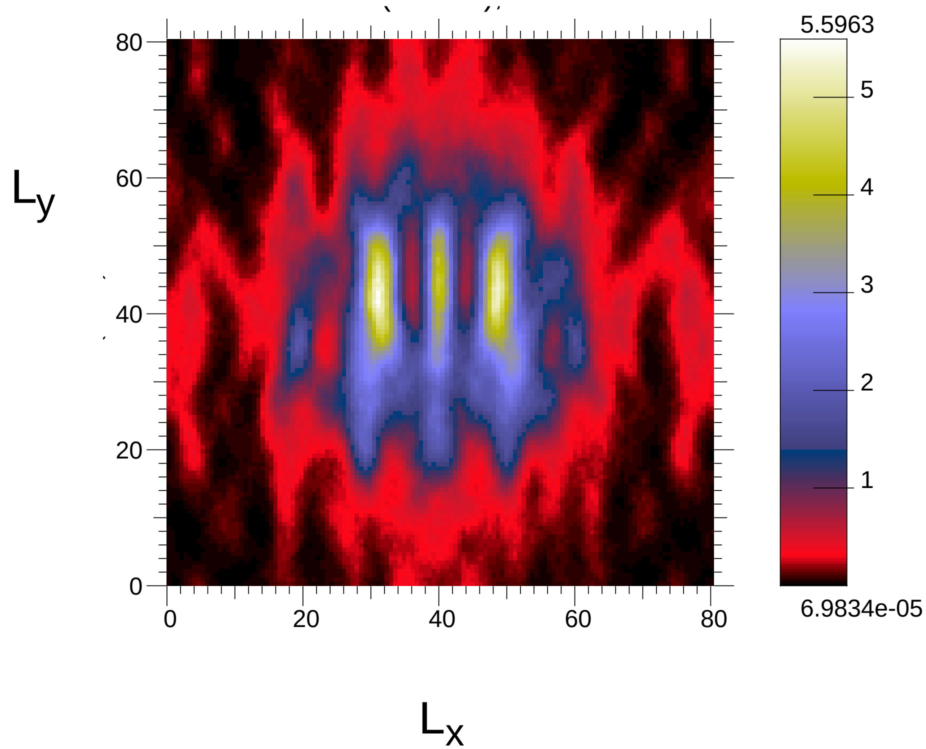
Ref: Physics of Plasmas, **6**, 2041 (1999);

B.Lasinski,A.B.Langdon,S.Hatchett,M.Key,M.Tabak,LLNL

3-D Massively Parallel Simulation of Laser Beam Breakup

Plot of $\mathbf{E}^2$ in the indicated plane from a 3-D MPP simulation (0.1 n_c, 2 x 10^{19} W/cm^2) at 225 fs which shows beam breakup.





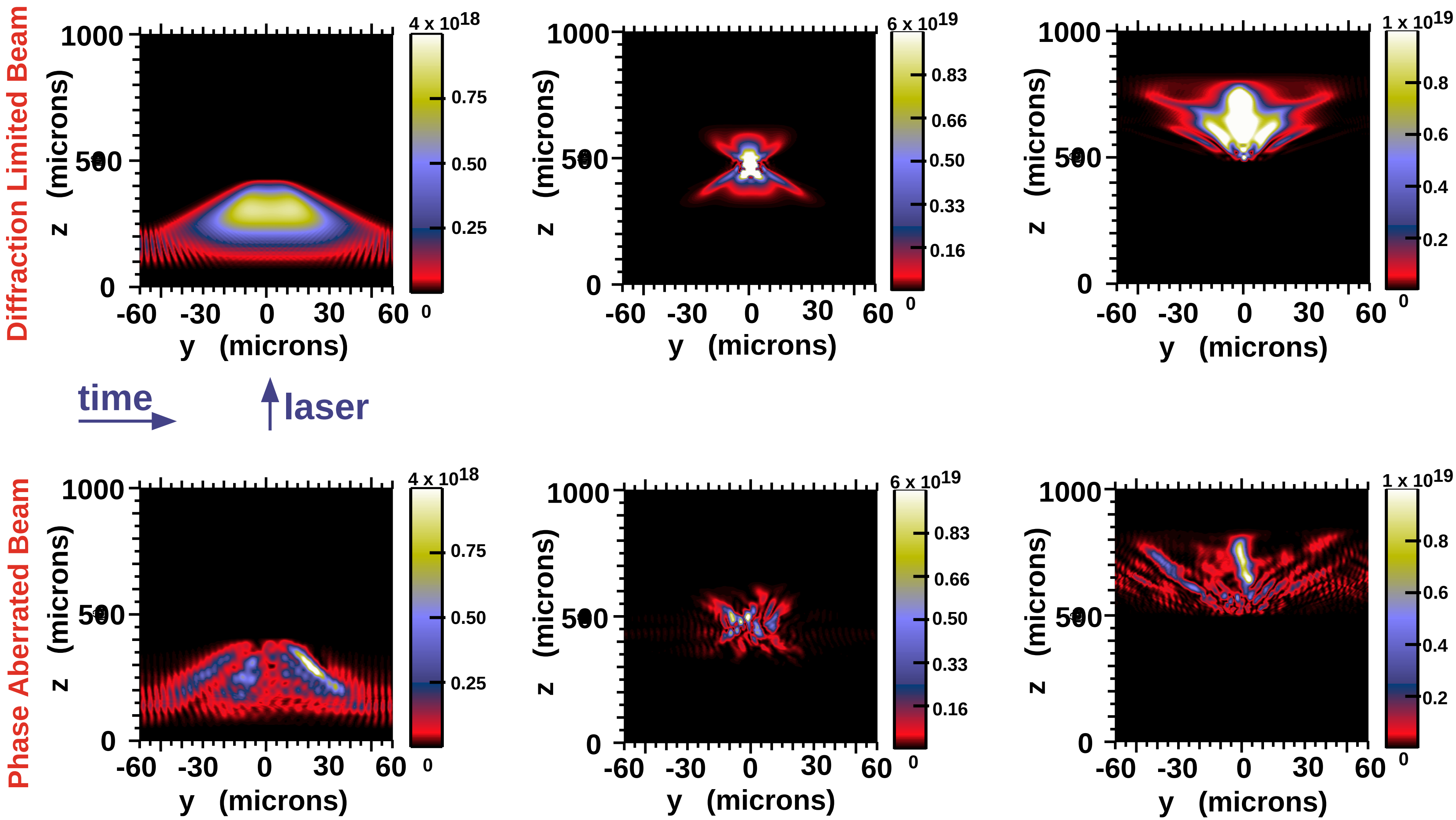
- The incident beam is linearly polarized in the y-direction.

- The beam breakup recognizes the polarization direction.

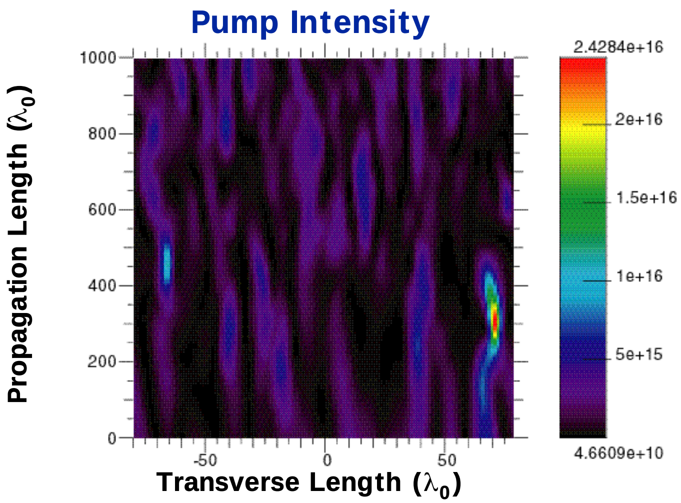
B.Lasinki,C.Still,A.B.Langdon,S.Hatchett,D.E.Hinkel,LLNL

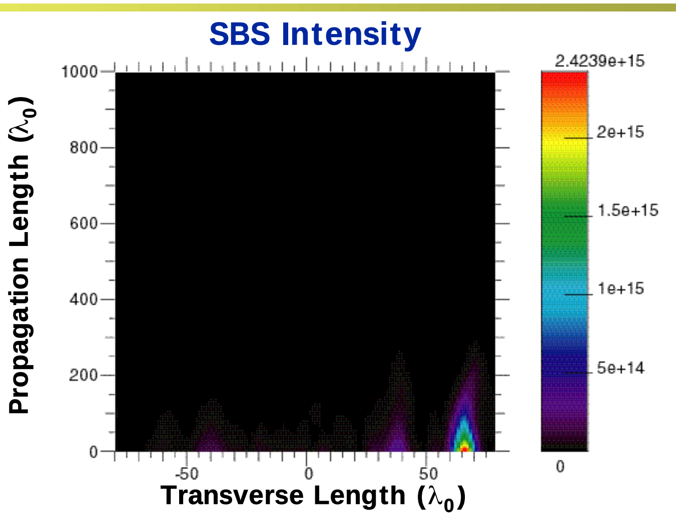
pF3d can propagate a laser pulse

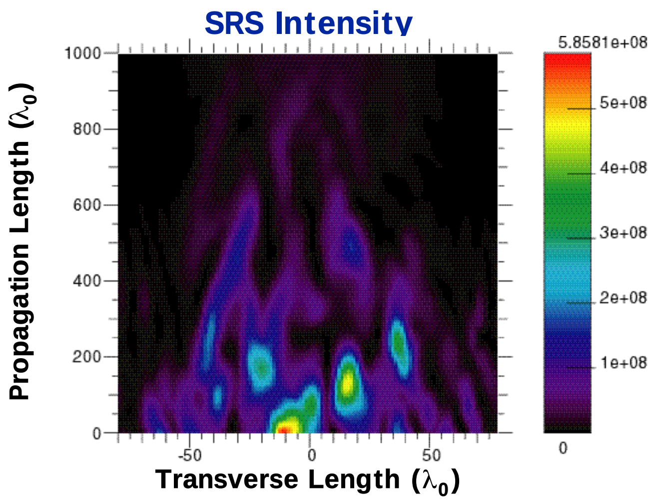
- simulations performed with new MPP F3D code - R. Berger, B. Still, et al.
- propagation of a 0.5 ps FWHM f/3 laser pulse with 105 TW of input power through 1 mm of n_e=0.01 - 0.03 n_c CH plasma:



3D Simulations of Raman and Brillouin run up to 100x faster than 2 years ago.

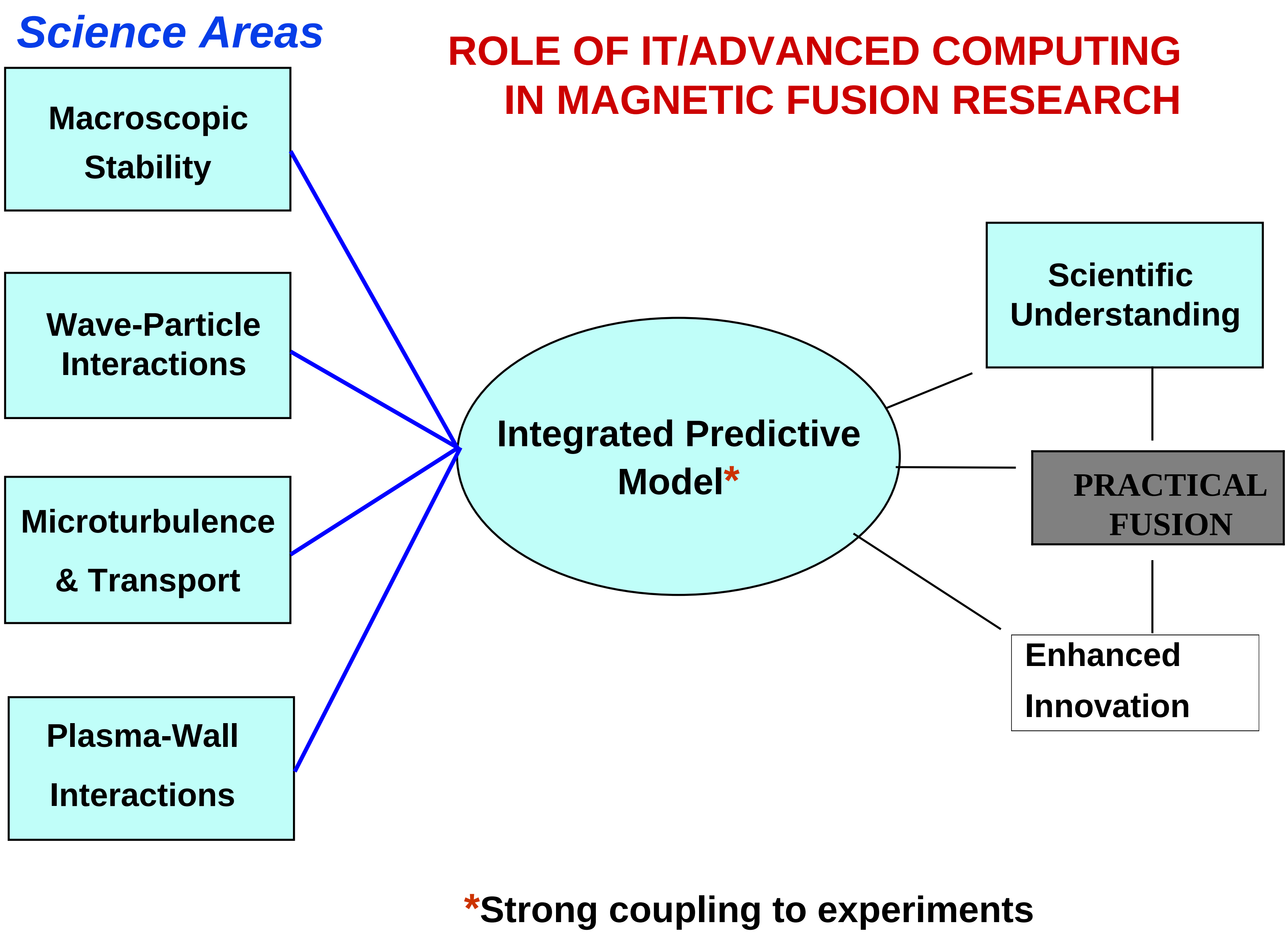






Simulating 20 ps of a 2 10^{15} W/cm^2 f/8 RPP 3ω laser in a 160λ_0 x 160λ_0 x 1000λ_0 C_5H_{12} plasma (T_e=3 keV, T_i=450 eV) using 32 cpus of the Compaq Alpha cluster took 12 hours. The same simulation needed over 1000 hours on 1 DEC Alpha cpu in March-May 1998.

Magnetic fusion

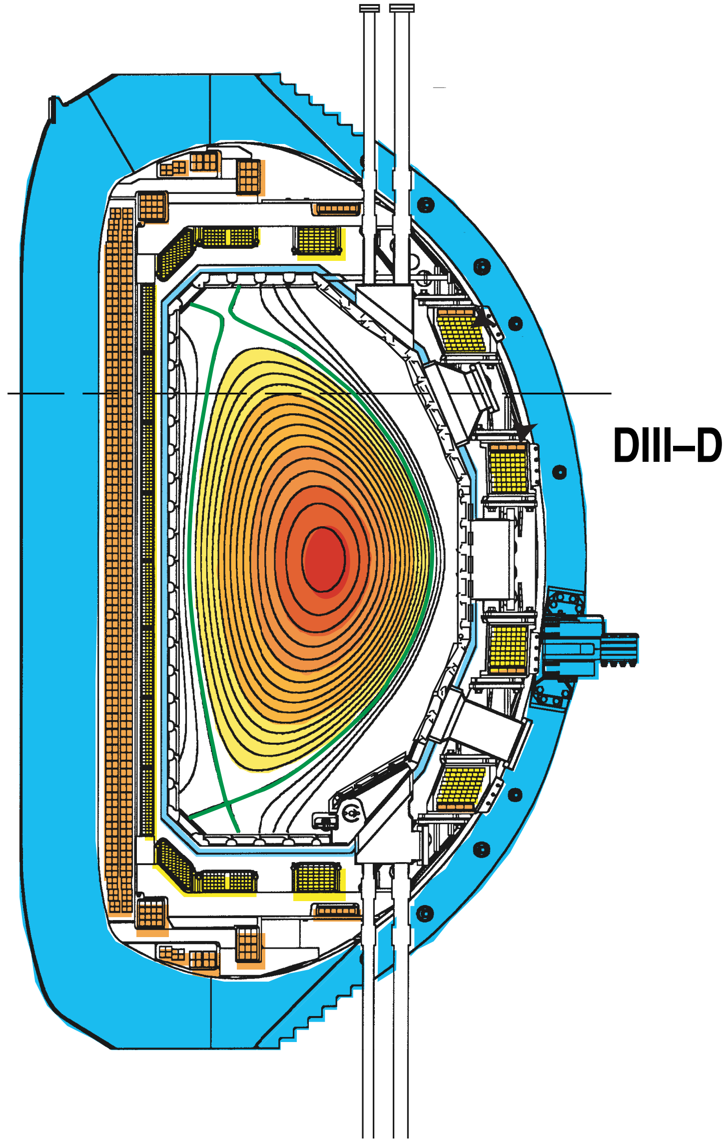

Science Areas
ROLE OF IT/ADVANCED COMPUTING
IN MAGNETIC FUSION RESEARCH
Macroscopic Stability
Wave-Particle Interactions
Microturbulence & Transport
Plasma-Wall Interactions
Integrated Predictive Model*
Scientific Understanding
PRACTICAL FUSION
Enhanced Innovation
*Strong coupling to experiments

PLASMA EQUILIBRIUM THEORY IS WELL UNDERSTOOD AND EXTENSIVELY USED

- Ampere's Law and the force balance equation $\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$ and $\vec{\nabla} P = \vec{J} \times \vec{B}$ lead to the Grad-Shafranov equation for the poloidal flux function.

  Equilibrium codes solve this equation for the closed flux contours that give the tokamak its good confinement.

- Such codes are used extensively in
  - Experiment design, control of complex shapes is precise
  - On-line data analysis $W(t)$, $\beta(t)$, $\tau_E(t)$
  - Providing the geometry for transport analysis



UNDERSTANDING TURBULENT PLASMA TRANSPORT

An important problem: Size of plasma ignition experiment determined by fusion self-heating $\Leftrightarrow$ turbulent transport losses

A scientific *Grand Challenge* problem

A true terascale computational problem for MPP's

The Numerical Tokamak Project
Simulation Of Tokamak Turbulent Transport: A Grand Challenge In Plasma Physics

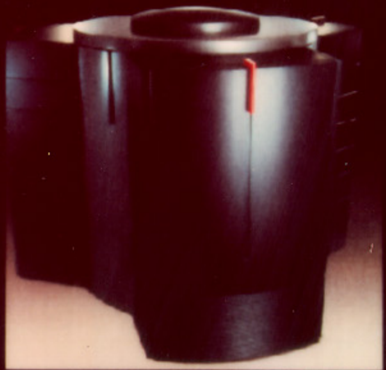
Consortium Participants

General Atomics
University Of Texas At Austin
University Of California At Los Angeles
Princeton Plasma Physics Laboratory
Jet Propulsion Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
National Energy Research Supercomputer Center
Oak Ridge National Laboratory

Numerical Tokamak Project Goals

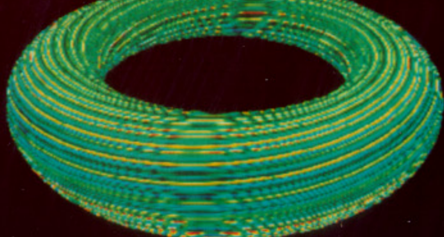
Short Term: Reliable prediction of tokamak core turbulence
Long Term: Reliable prediction of tokamak performance
Approach: Develop the most advanced computational models of tokamak physics using the most powerful high performance computing and communications environments in a multi–institutional, multi–disciplinary collaboration.

Computational Model Development
C90 NERSC



ESNET

Data Generation
CM5 ACL



Data Storage
Retrieval
NSL ACL

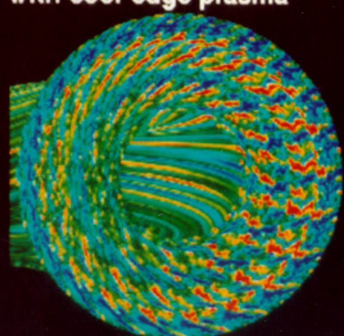
ESNET

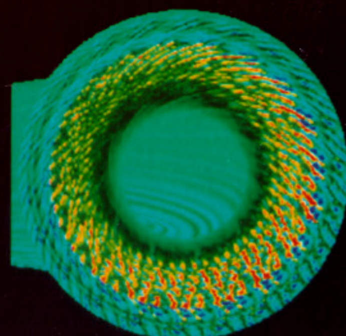
Distributed Visualization
CM5 AVS SGI
NERSC ACL

Scientific Issues

Fusion ignition prevented by turbulent mixing of hot core plasma with cool edge plasma

Numerically explore conditions which reduce turbulence

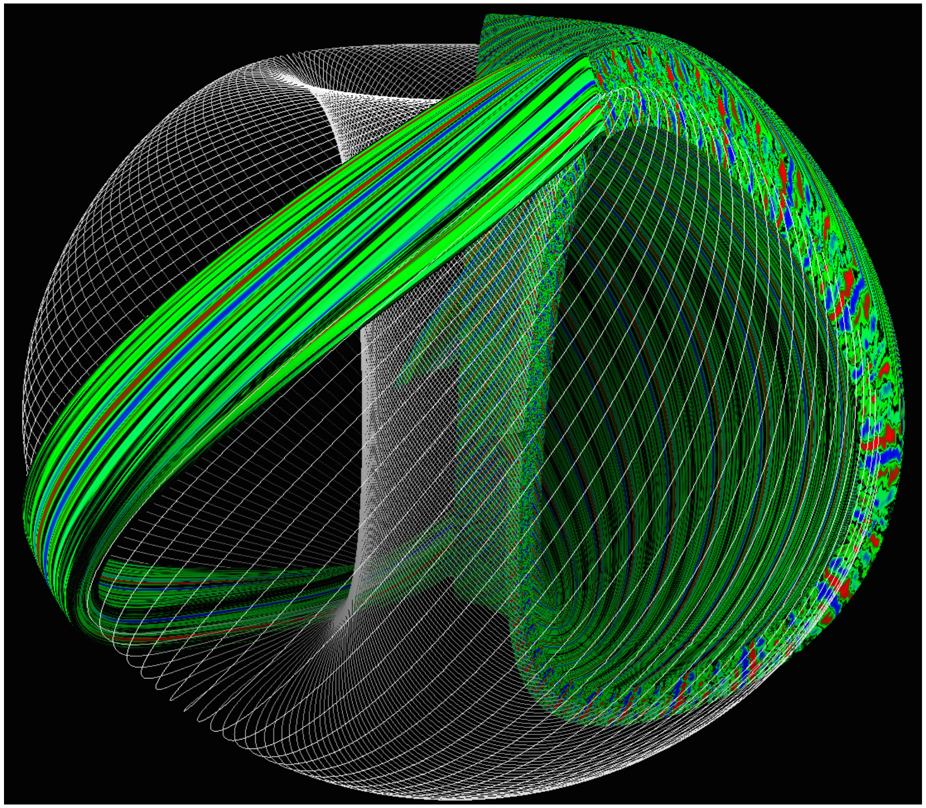




Create better physical models for tokamak plasma turbulence

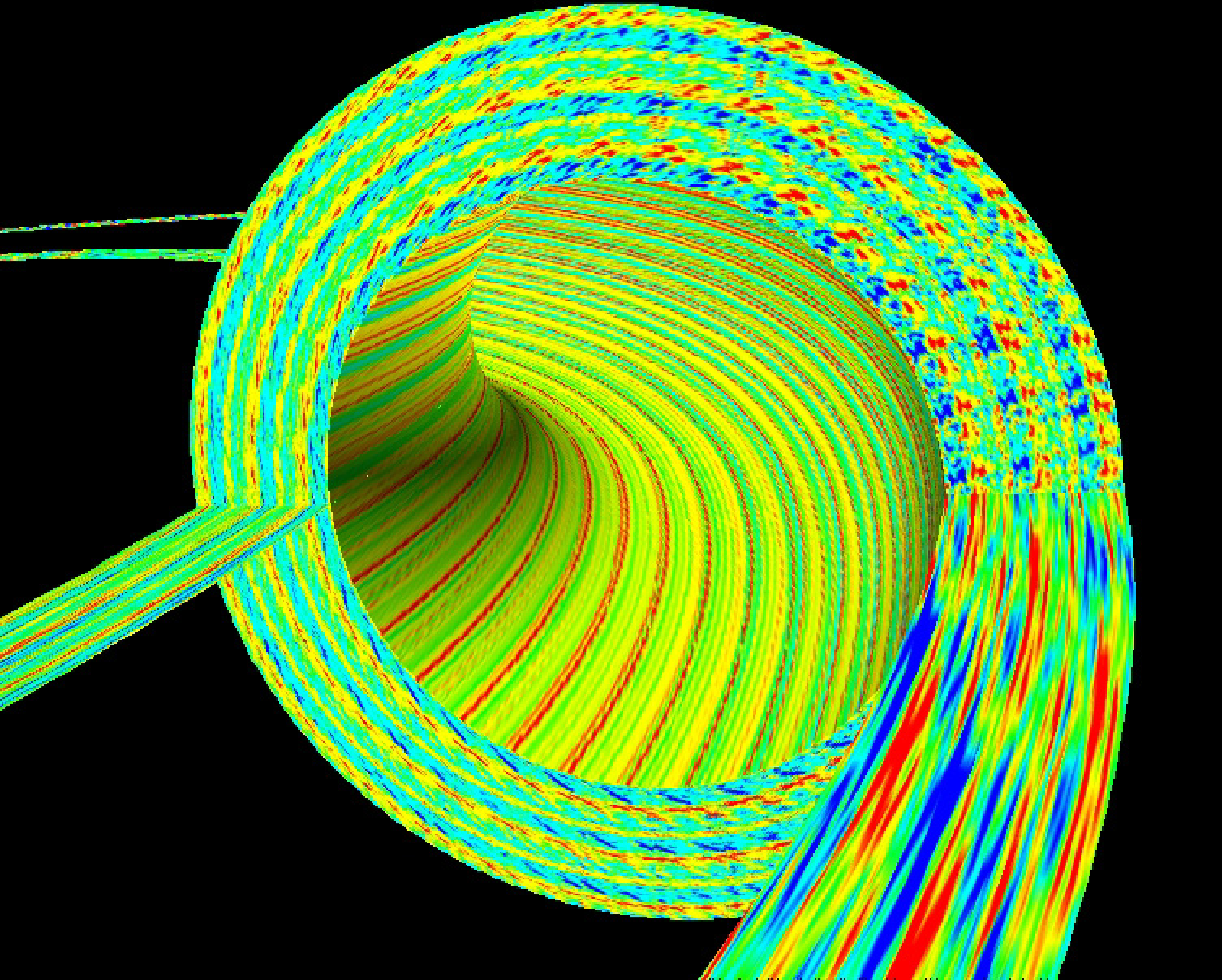
PLASMA TURBULENCE SIMULATIONS

- **Realistic Geometry**
  - **Full Torus (3D)**
  - **Flux Tube Codes**
- **Efficient Algorithms**
  - **Gyrofluid --- *Landau Closures***
  - **Gyrokinetic --- *PIC***
- **Demonstrated scaling to many processors**



3D Gyrokinetic Magnetic Flux-tube Simulation of Tokamak Turbulence

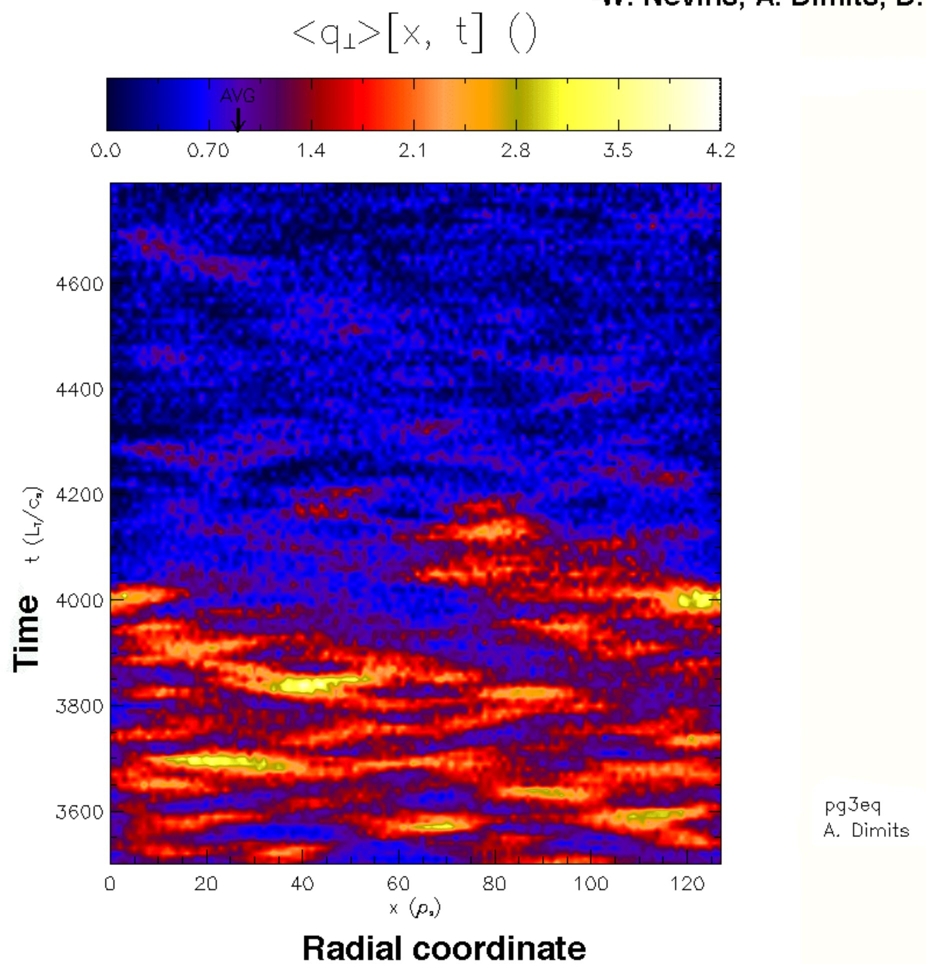
A. Dimits, T. Williams, J. Byers, B. Cohen, D. Shumaker, W. Nevins, LLNL



The Plasma Microturbulence Project Uses Massively Parallel 3-D Simulations To Better Understand Heat Transport in Tokamak Fusion Plasmas

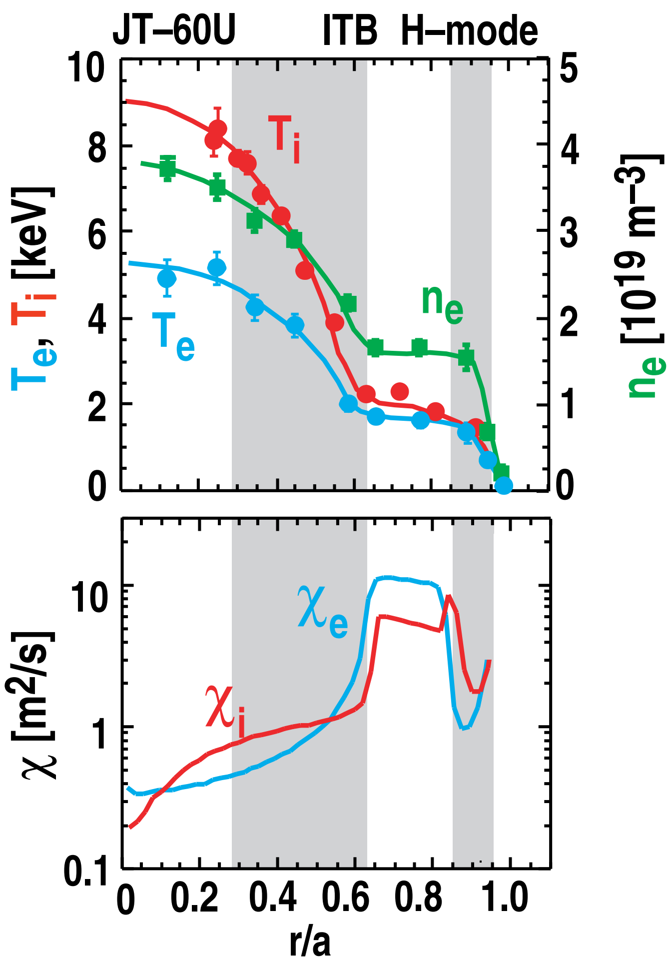
-W. Nevins, A. Dimits, D. Shumaker, LLNL

Radial Heat Flux

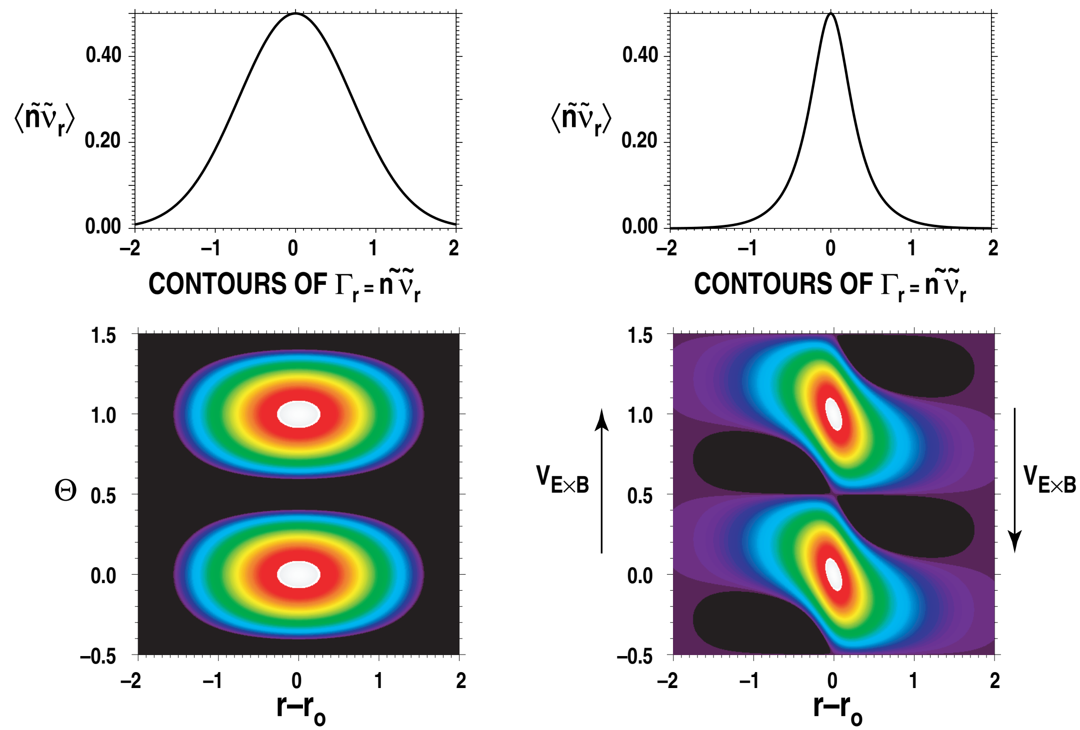


Radial heat flux vs. radius and time. There is a transition at t=4100 from high heat flux to improved confinement with low heat flux.

RECENT EXCITEMENT
TRANSPORT BARRIERS FORMED BY SHEARED E×B FLOW



Basic Idea: Sheared E×B flow compresses turbulent eddies in the radial direction

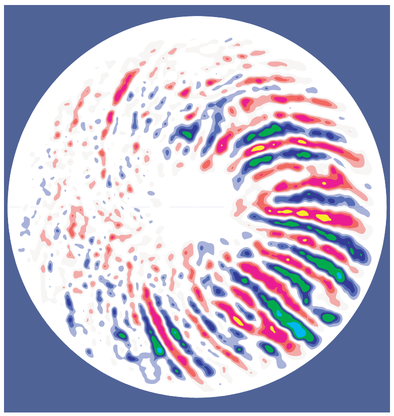


Stambaugh, GA

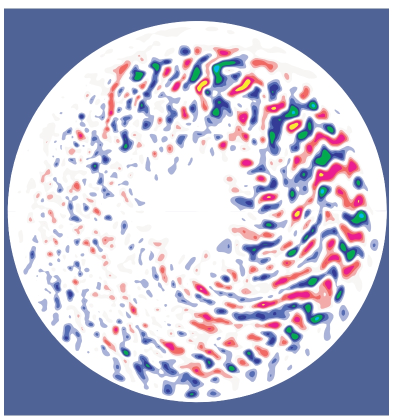
PLASMA TURBULENCE SIMULATION CODES USE FULL TOROIDAL GEOMETRY TO CALCULATE TRANSPORT RATES

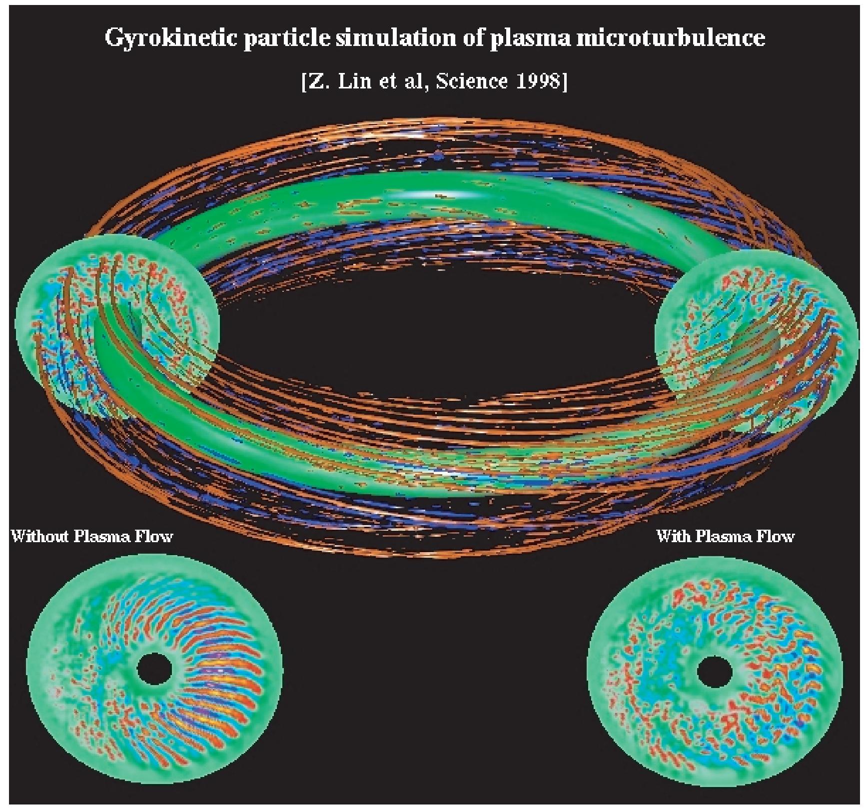
- **Recent advance: Small scale sheared poloidal flows can shear apart radial eddies, reducing their radial step size and the transport by an order of magnitude - Z. Lin, PPPL**

Without sheared flows

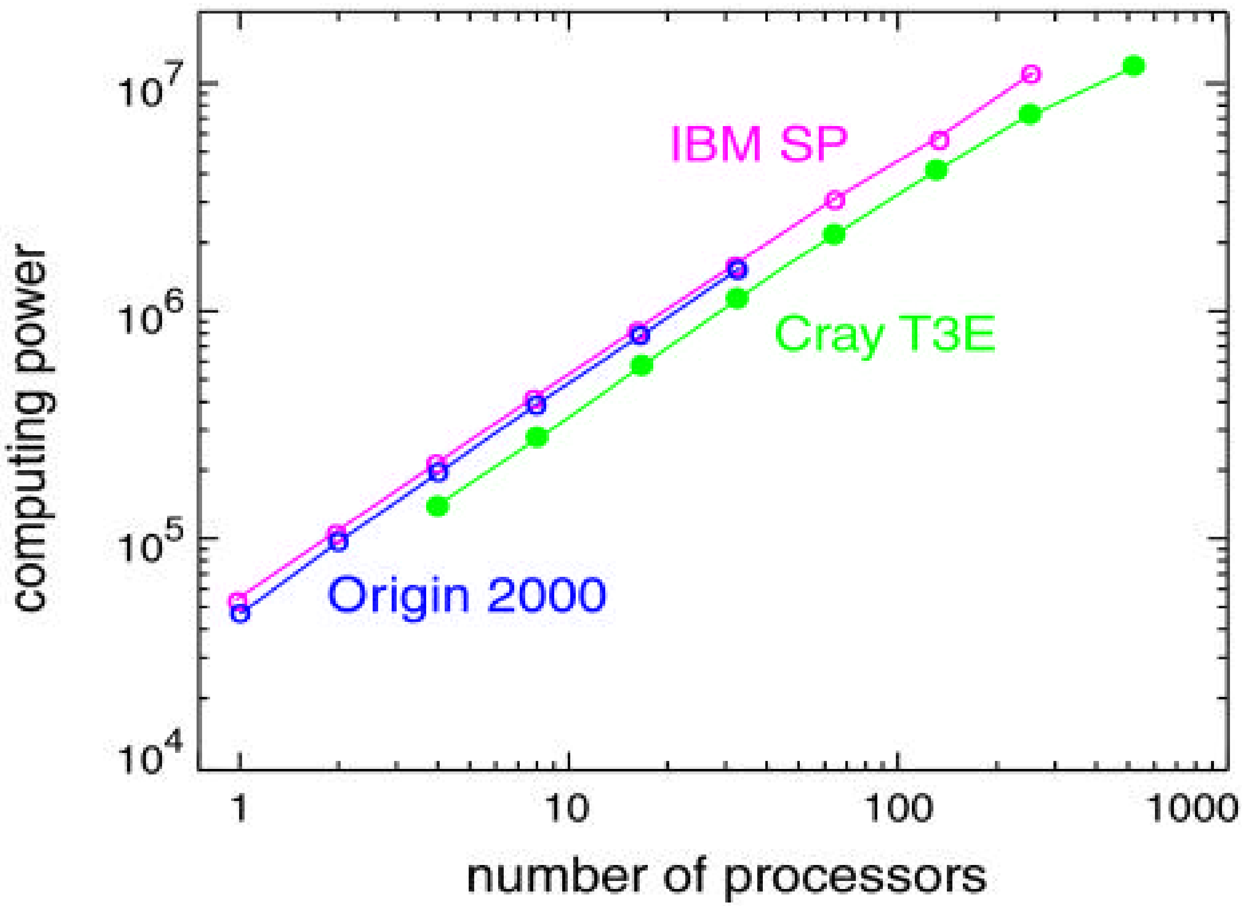


With sheared flows





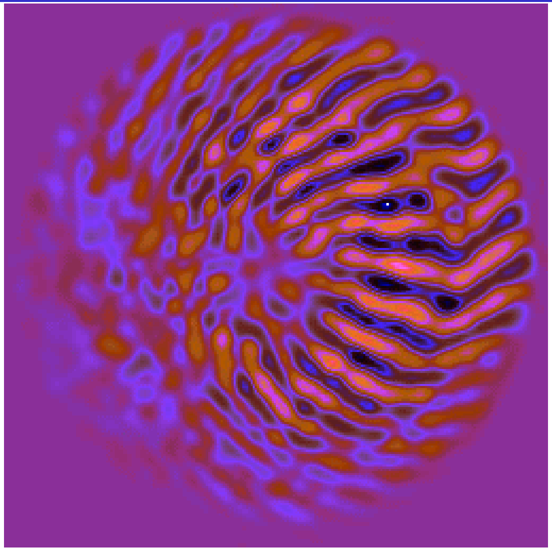
3D Gyrokinetic Turbulence Code (GTC) Scalable on Massively Parallel Computers



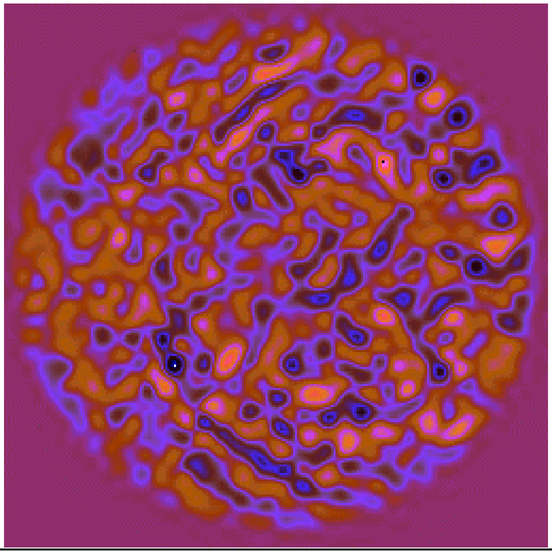
- Y-axis: the number of particles which move 1 step in 1 second

Example of tokamak turbulence simulation

- Contour plot of potential fluctuations
- Early linear stage shows long radial structures.
- Later, non-linear stage shows much shorter radial structures.
- Simulations performed by J.-N. Leboeuf, UCLA

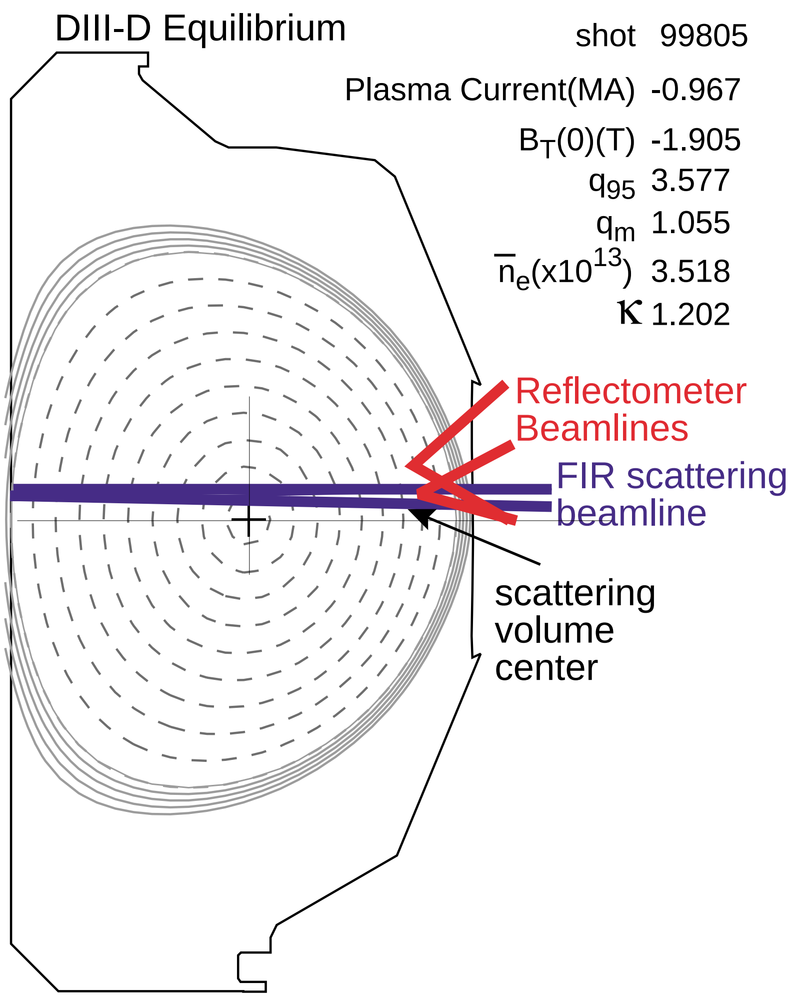


Linear Phase



Nonlinear Steady State

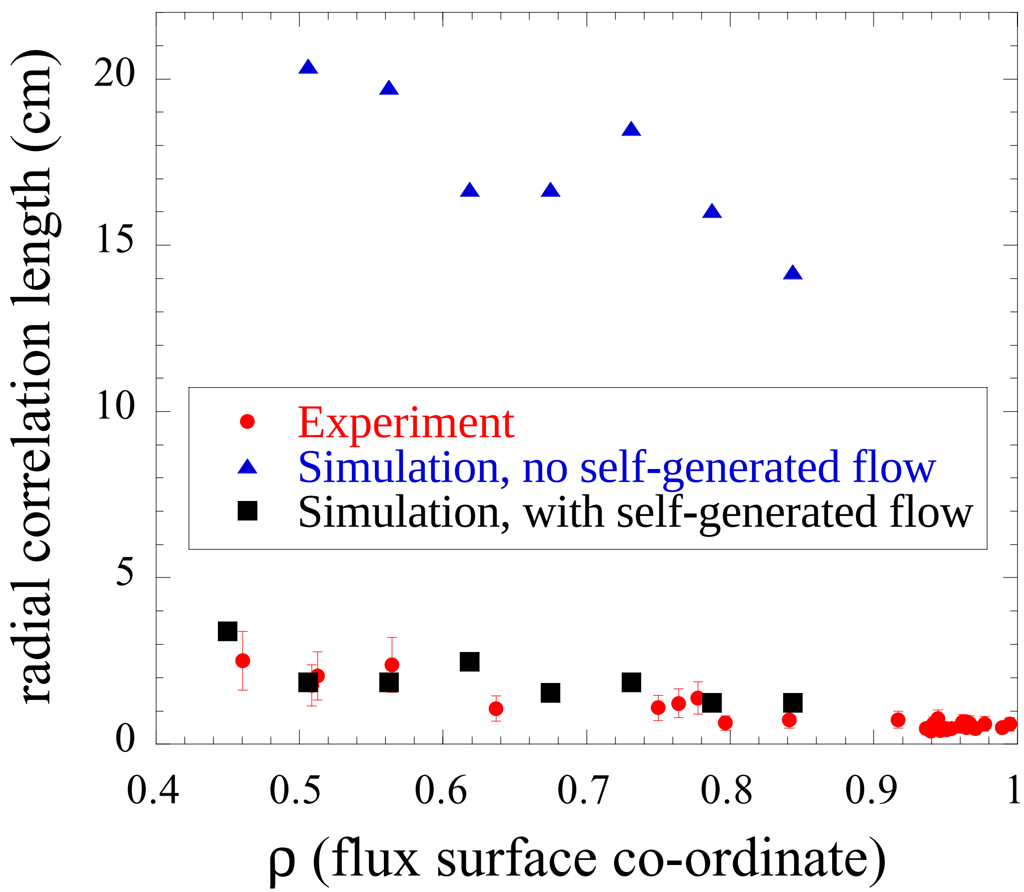
Part III: Experiment designed to investigate existence of ITG on DIII-D



- Circular, ohmic discharges.
- Density scanned from 0.8 to $4x10^{13}cm^{-3}$.

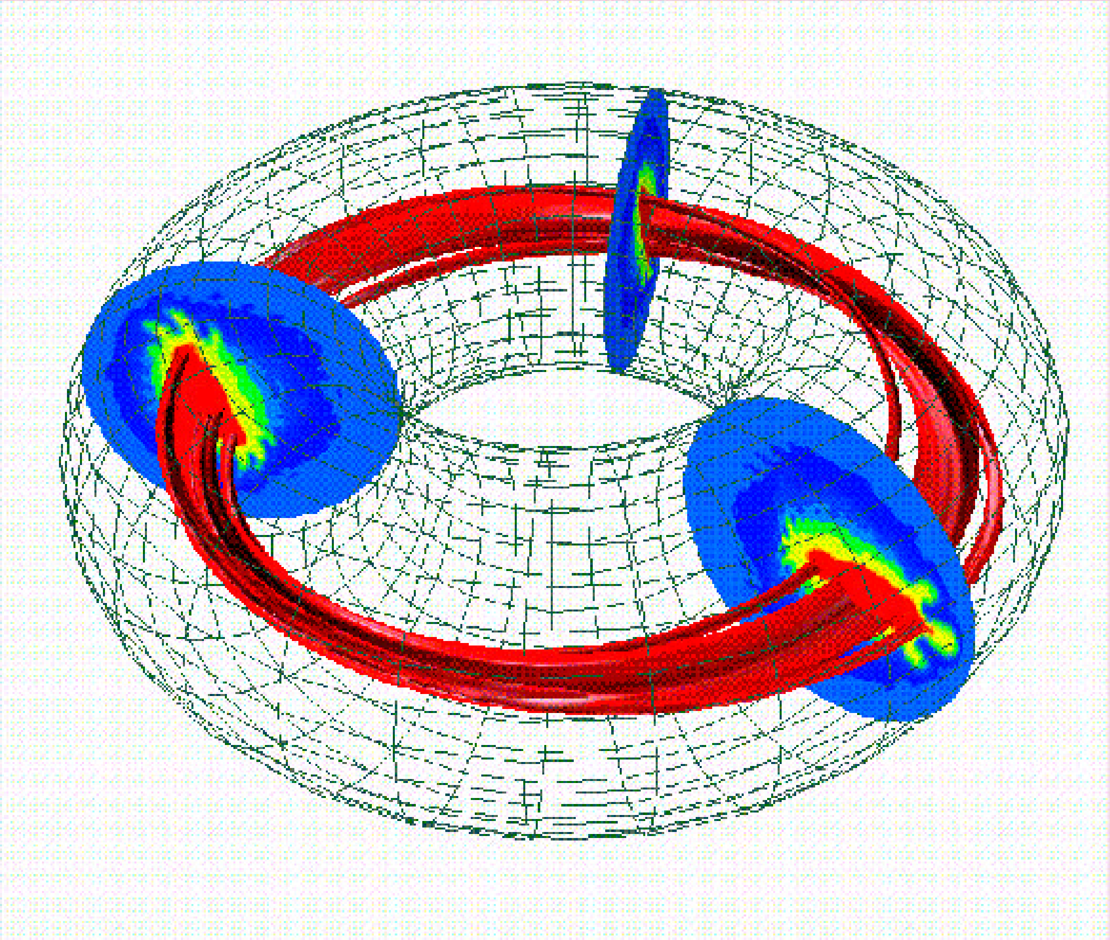
Numerical model: Δr with zonal flows comparable to experiment values

Simulations performed by J-N. Leboeuf



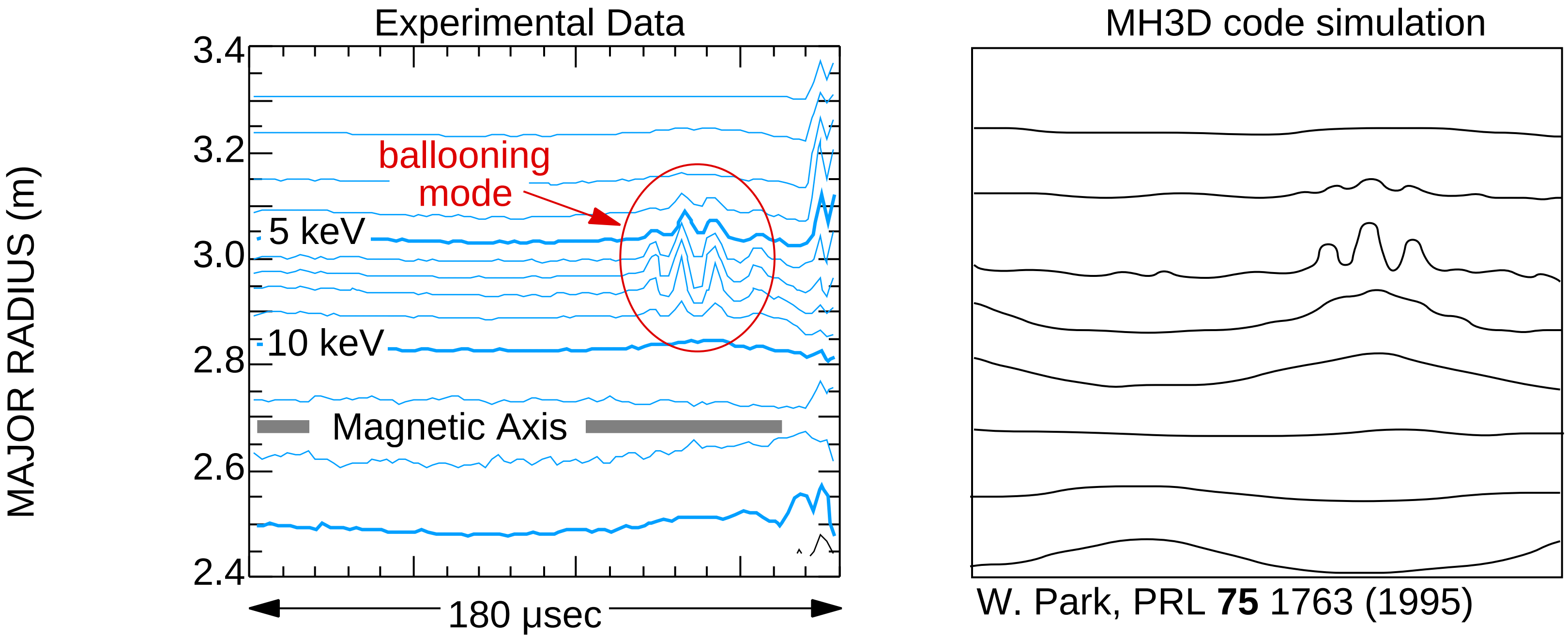
- With zonal flows the numerically determined lengths drop to near the measured Δr.
- Although agreement is intriguing this is a very early stage of the comparison and more work remains.
- For example, the plasmas simulated are circular while the real plasmas were shaped
- A fully shaped code is currently being utilized and broader, more complete comparisons are in progress.

3D SIMULATION OF HIGH PLASMA PRESSURE-DRIVEN DISRUPTION



NONLINEAR 3D-FLUID COMPUTATIONS

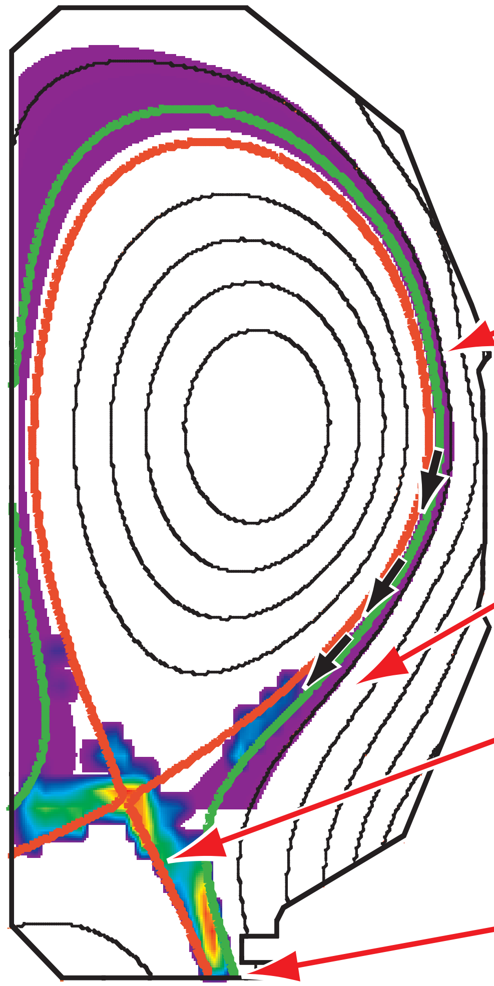
Successful Simulation of the Complex Interplay Between n=1 Kink and Ballooning Modes



W. Park, PRL **75** 1763 (1995)

- Nonlinear numerical simulations find n=1 kink drives local ballooning modes unstable leading to disruptive collapse

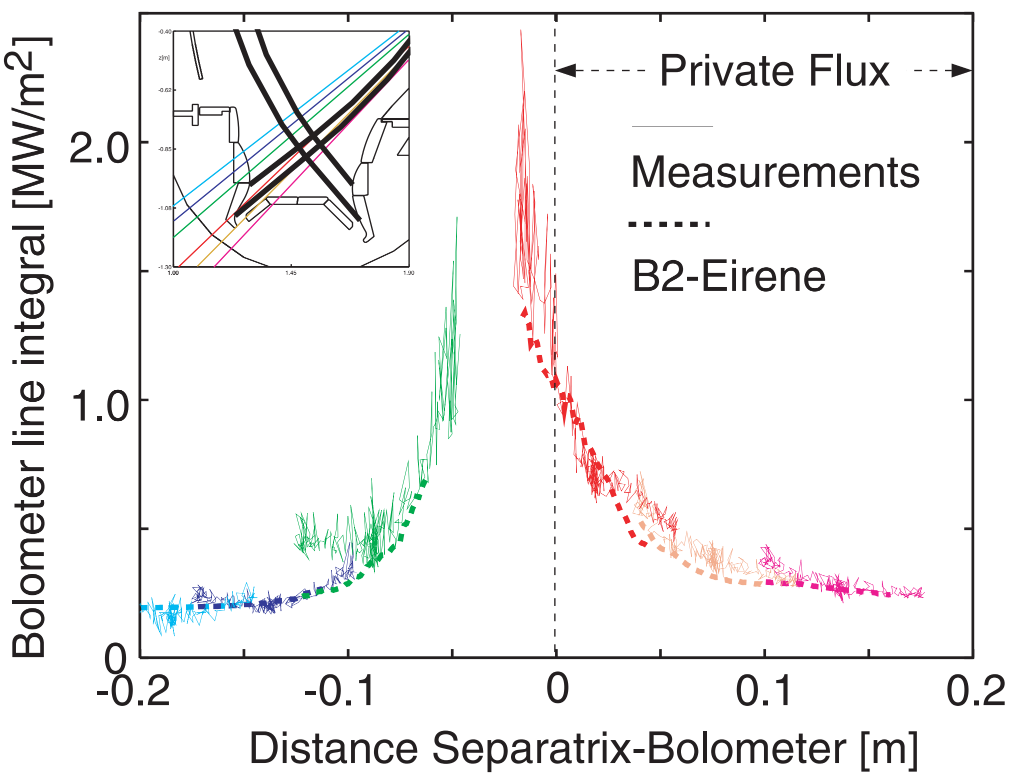
THE PHYSICS ELEMENTS THAT ARE DOMINANT IN THE DIVERTOR PROBLEM ARE NOW INCORPORATED IN 2-D CODES

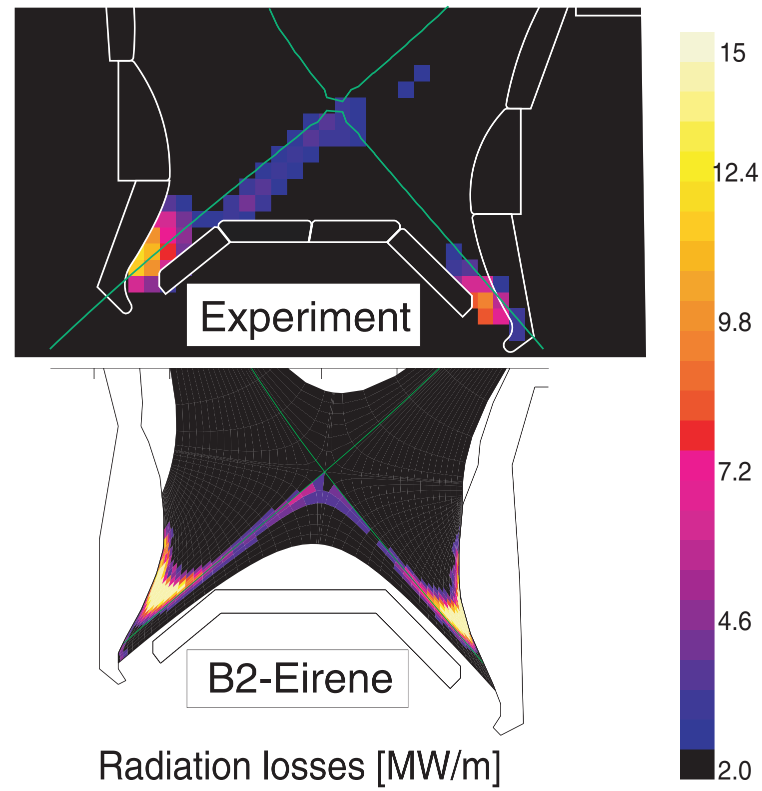


- Strong parallel transport
  Fluid drifts
  Actual flux surface geometry
- Non-equilibrium radiation rates
  2-D flow patterns
- Neutral recycling
  Recombination
  Detailed divertor structures
- Erosion of surfaces
  Ablation during intense heat pulses

AN EXAMPLE OF EXCELLENT AGREEMENT BETWEEN B2-E IRENE CALCULATED AND MEASURED RADIATION DISTRIBUTIONS

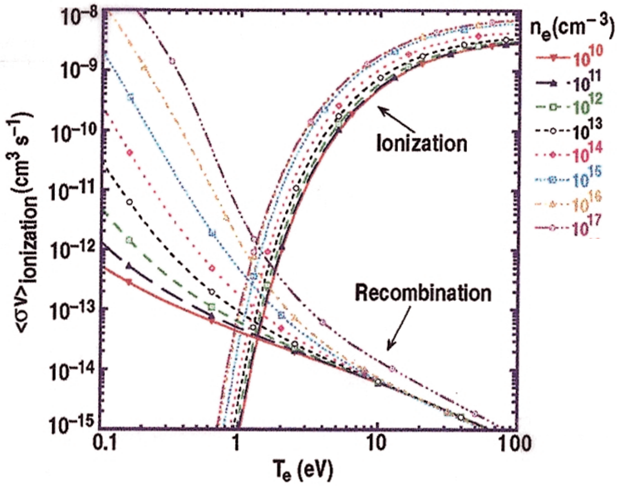
ASDEX–UPGRADE





Excellent agreement

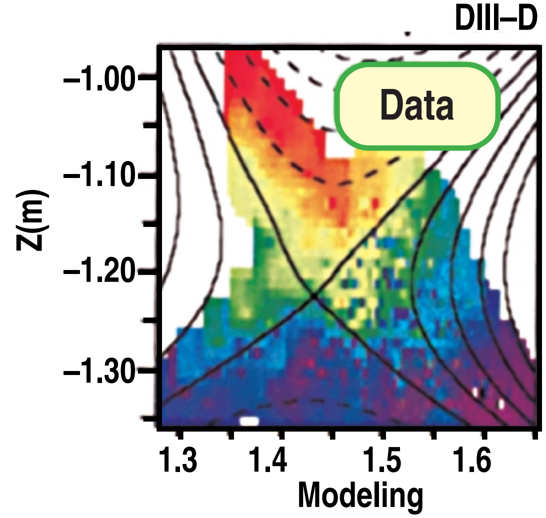
RECOMBINING DIVERTOR PLASMAS DISCOVERED



Alcator C–Mod

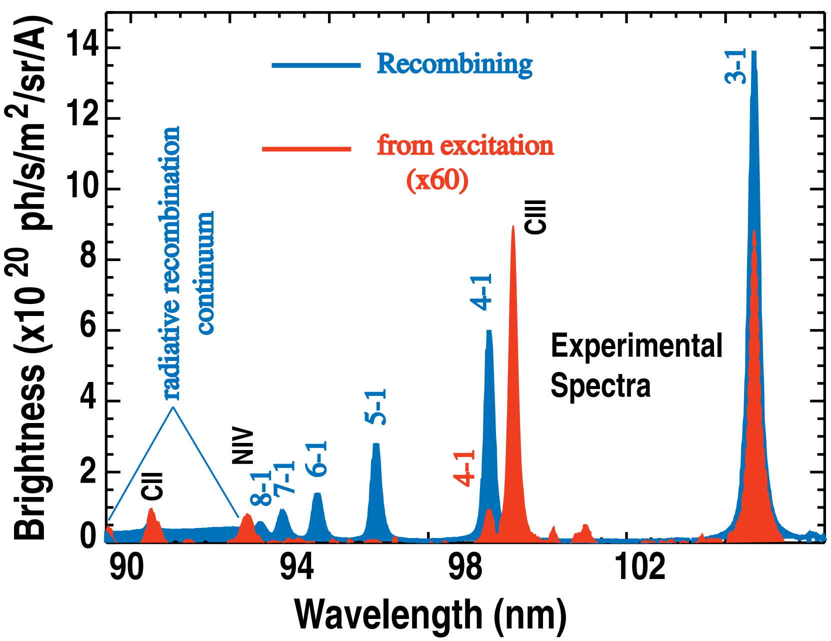
- T_e ~ 1 eV at divertor plate (probes)
- T_e 0.4-0.6 eV in divertor plasma (spect.)

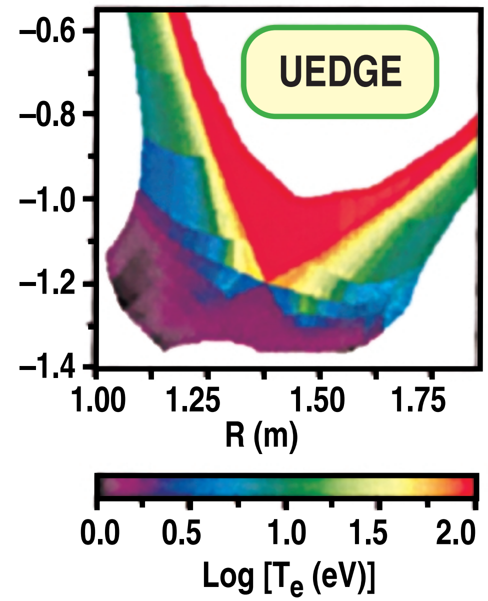
Low Electron Temperature



Scaling of Lyman Series Line Intensities Shows When the Upper Levels of the Lines Are Populated by **Recombination**

Alcator C–Mod





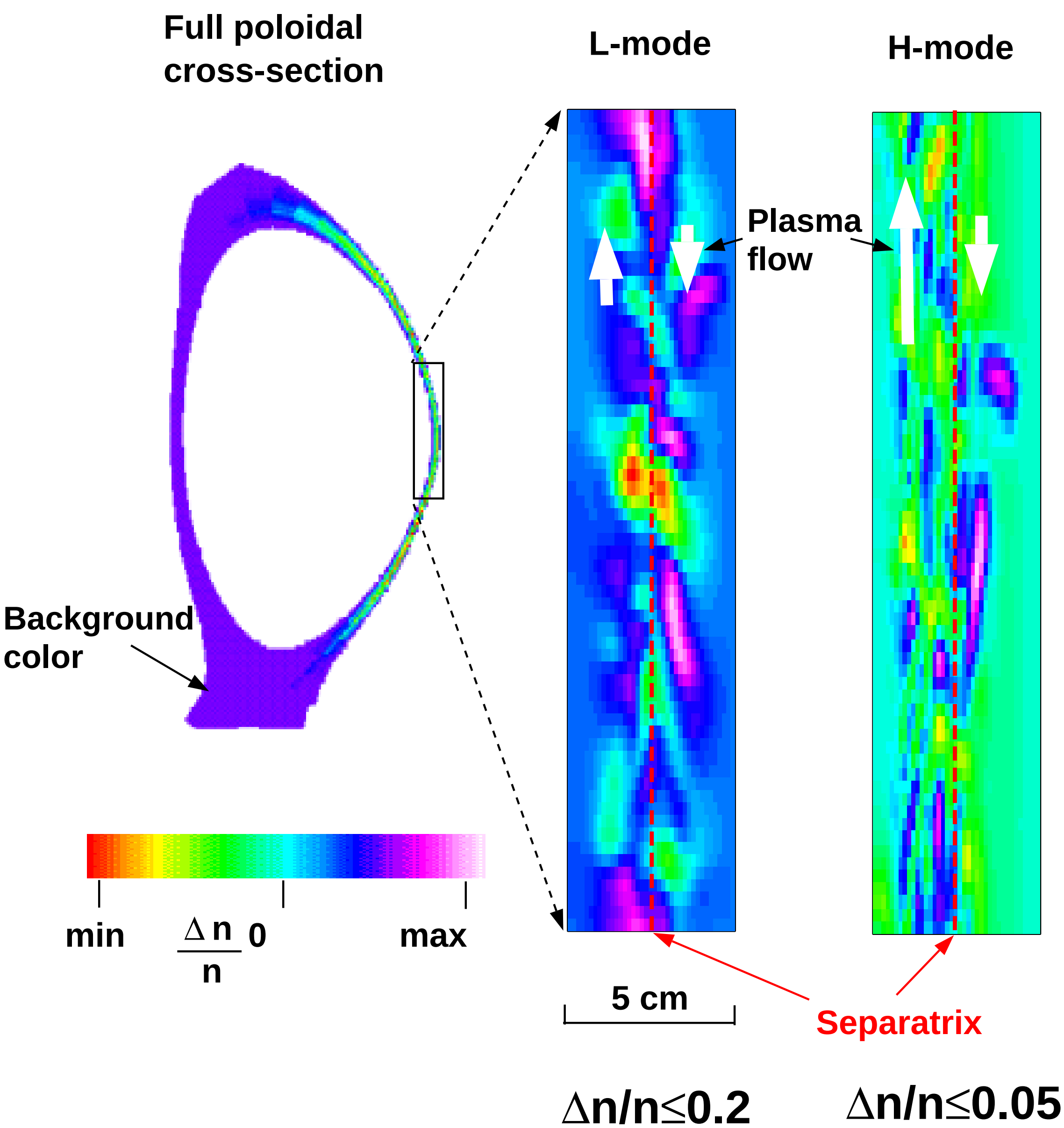
219-00/jy

MIT, GA, LLNL

3D turbulence simulations show large density fluctuations on outboard side

BOUT simulations by Xu, et al., Phys. Plasmas 7 (2000)

H-mode structures are broken up by flow shear



The Future of Supercomputing in Fusion Research

- The range of space and time scales in most plasmas will still far exceed the capabilities of hardware and algorithms to do direct, first-principles simulation in 3D + time.

- However, hardware capability (cpu speed, memory size and bandwidth, etc.) and algorithms will continue to improve dramatically so that researchers will be able to perform ever bigger and more realistic simulations.

- The cost of doing leading-edge (albeit “bleeding-edge”) computing will continue to remain small (≤ \$20-\$30M for the supercomputer) compared to the capital cost of a fusion ignition experiment (~\$1-\$2B). A relatively inexpensive, but realistic simulation capability can have immense leverage on relatively expensive experiments.

- The relevance of computer simulations of plasmas to experiment and plasma science in general is now well established and will continue to grow.

- Computer simulation of plasma phenomena is an equal partner to theory and experiment.